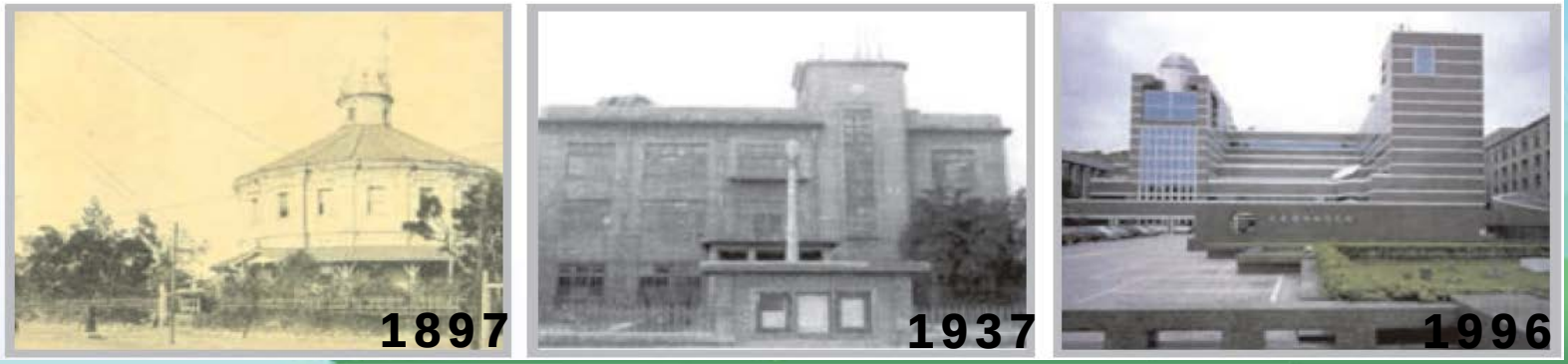
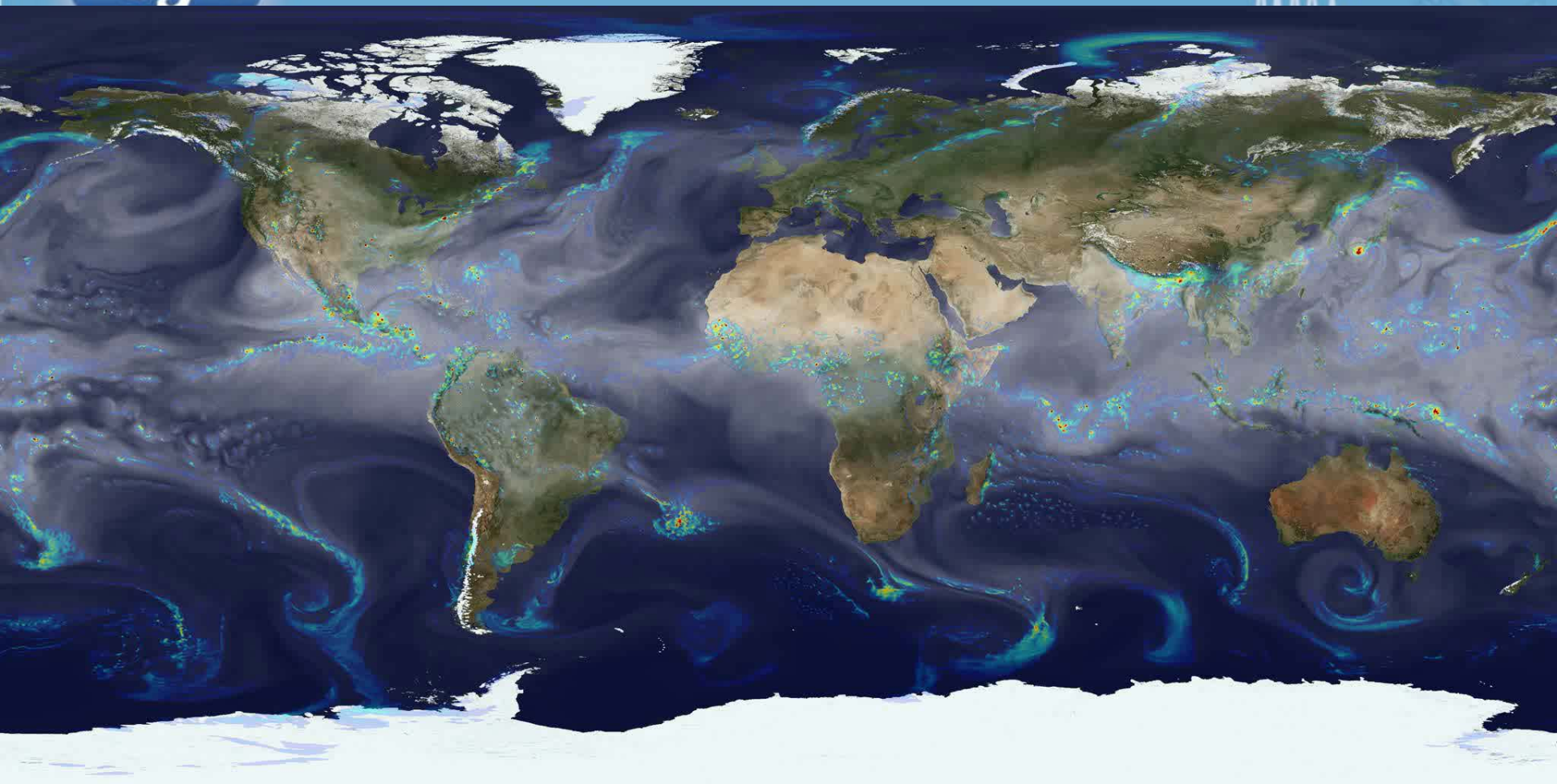
# 中央氣象局數值模式產品介紹及跨域應用經驗分享

洪景山
交通部中央氣象局



「數值天氣預報」是天氣預報的基礎
過去是，現在是，未來也將是

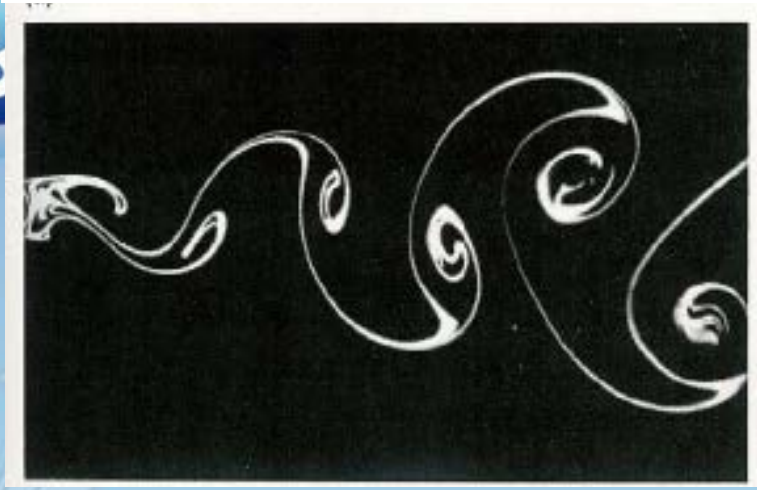
# 什麼是「數值天氣預報」



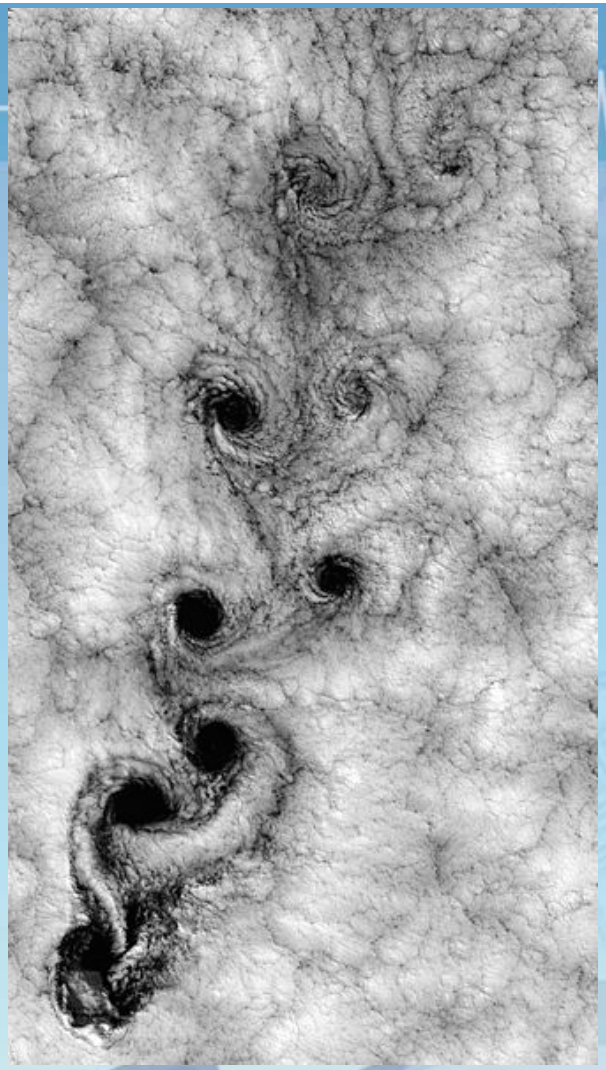
Atmospheric motion, looks like the flow of the fluid

Weather forecast: To predict the motion of the flow

Hydraulic experiment



Atmospheric observation



Numerical solution

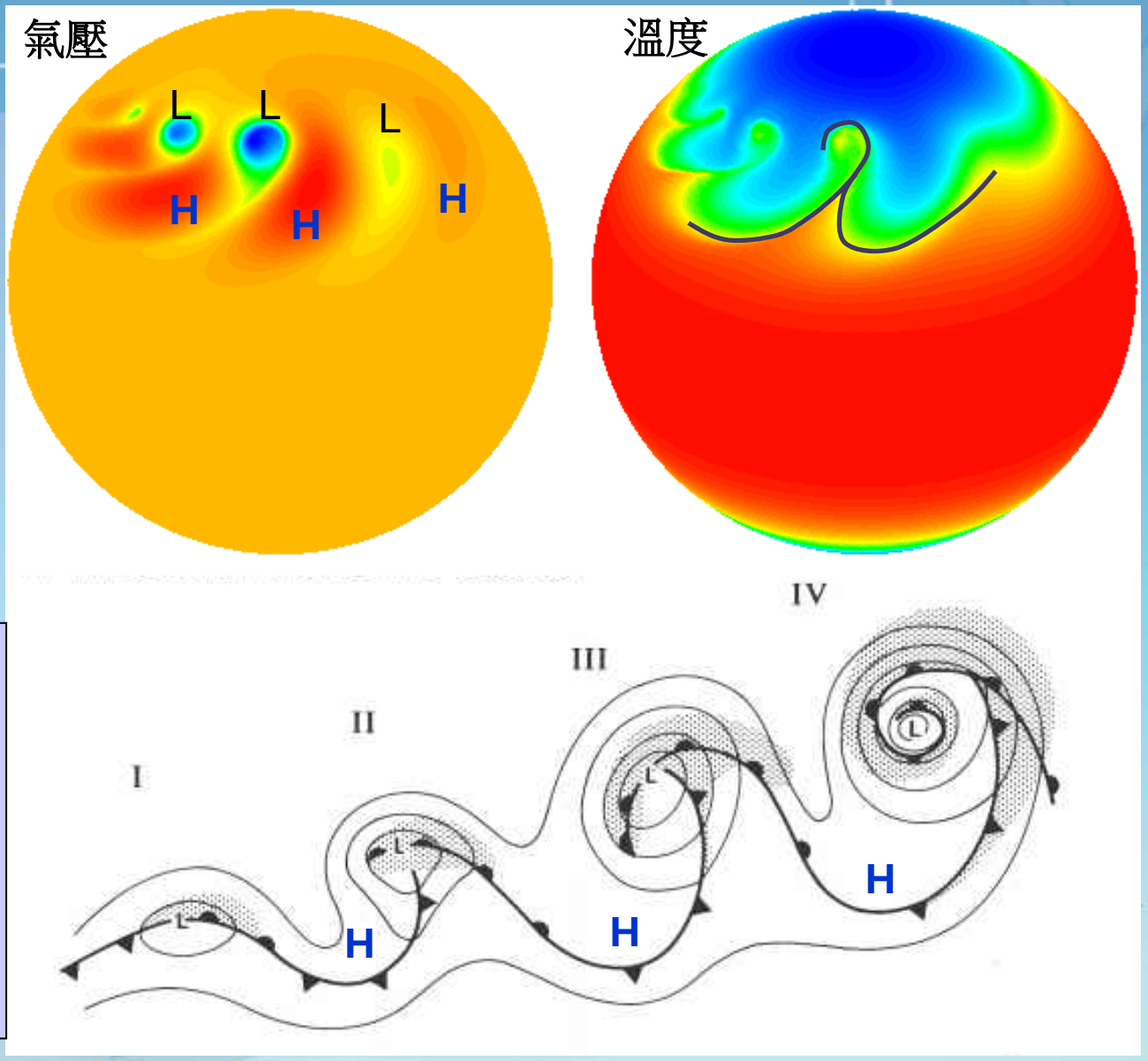
$$\frac{\partial}{\partial t} + H\frac{\partial}{\partial x} + H\frac{\partial}{\partial y} = 0$$

Shallow water equation

$$\frac{Du}{Dt} - fv = -g\frac{\partial \eta}{\partial x}$$

$$\frac{Dv}{Dt} + fu = -g\frac{\partial \eta}{\partial y}$$

$$\frac{\partial \eta}{\partial t} + H\frac{\partial u}{\partial x} + H\frac{\partial v}{\partial y} = 0$$



# Equations to govern the atmospheric motion

$$\partial_t U + (\nabla \cdot \mathbf{V}u)_\eta + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \phi = F_U$$
$$\partial_t V + (\nabla \cdot \mathbf{V}v)_\eta + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \phi = F_V$$
$$\partial_t W + (\nabla \cdot \mathbf{V}w)_\eta - g[(\alpha/\alpha_d)\partial_\eta p - \mu_d] = F_W$$
$$\partial_t \Theta + (\nabla \cdot \mathbf{V}\theta)_\eta = F_\Theta$$
$$\partial_t \mu_d + (\nabla \cdot \mathbf{V})_\eta = 0$$
$$\partial_t \phi + \mu_d^{-1}[(\mathbf{V} \cdot \nabla \phi)_\eta - gW] = 0$$
$$\partial_t Q_m + (\mathbf{V} \cdot \nabla q_m)_\eta = F_{Q_m}$$

$$\partial_t U + m[\partial_x(Uu) + \partial_y(Vu)] + \partial_\eta(\Omega u) + (\mu_d \alpha \partial_x p' + \mu_d \alpha' \partial_x \bar{p}) + (\alpha/\alpha_d)(\mu_d \partial_x \phi' + \partial_\eta p' \partial_x \phi - \mu_d' \partial_x \phi) = F_U \tag{2.35}$$

$$\partial_t V + m[\partial_x(Uv) + \partial_y(Vv)] + \partial_\eta(\Omega v) + (\mu_d \alpha \partial_y p' + \mu_d \alpha' \partial_y \bar{p}) + (\alpha/\alpha_d)(\mu_d \partial_y \phi' + \partial_\eta p' \partial_y \phi - \mu_d' \partial_y \phi) = F_V \tag{2.36}$$

$$\partial_t W + m[\partial_x(Uw) + \partial_y(Vw)] + \partial_\eta(\Omega w) - m^{-1} g(\alpha/\alpha_d)[\partial_\eta p' - \bar{\mu}_d(q_v + q_c + q_r)] + m^{-1}\mu_d' g = F_W, \tag{2.37}$$

and the mass conservation equation (2.27) and geopotential equation (2.28) become

$$\partial_t \mu_d' + m^2[\partial_x U + \partial_y V] + m\partial_\eta \Omega = 0 \tag{2.38}$$

$$\partial_t \phi' + \mu_d^{-1}[m^2(U\phi_x + V\phi_y) + m\Omega\phi_\eta - gW] = 0. \tag{2.39}$$

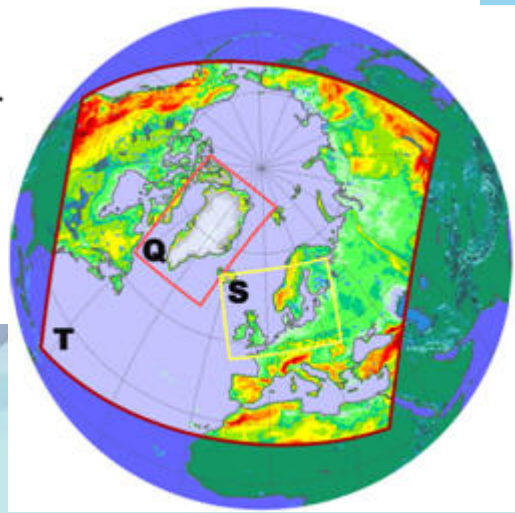
Remaining unchanged are the conservation equations for the potential temperature and scalars

$$\partial_t \Theta + m^2[\partial_x(U\theta) + \partial_y(V\theta)] + m\partial_\eta(\Omega\theta) = F_\Theta$$

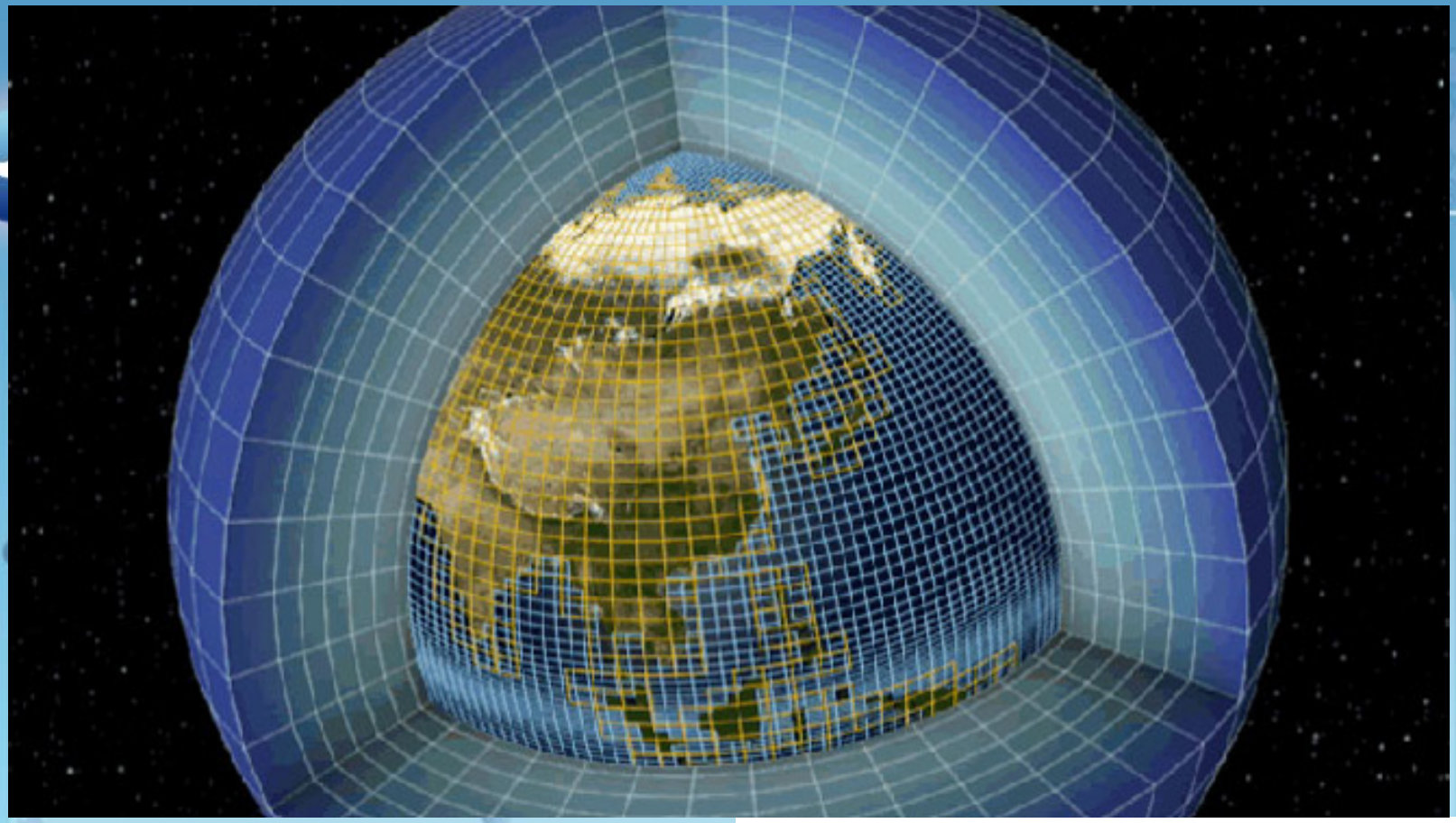
$$\partial_t Q_m + m^2[\partial_x(Uq_m) + \partial_y(Vq_m)] + m\partial_\eta(\Omega q_m) = F_{Q_m}.$$

In the perturbation system the hydrostatic relation (2.30) becomes

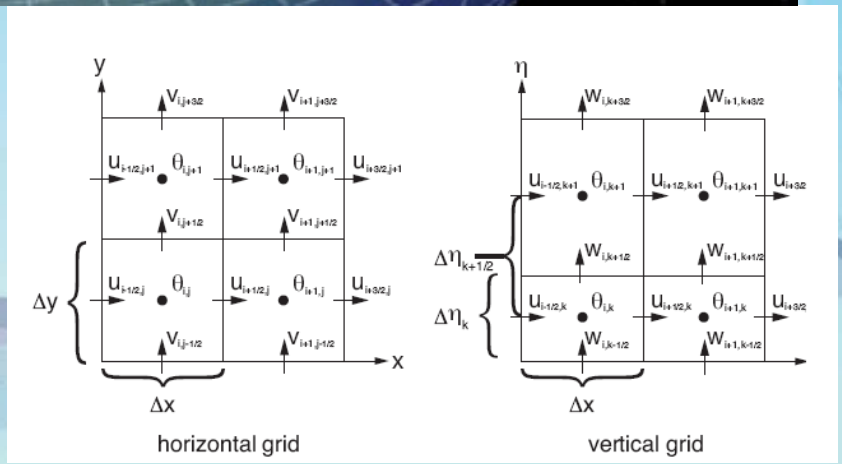
$$\partial_\eta \phi' = -\bar{\mu}_d \alpha_d' - \alpha_d \mu_d'.$$




Project to the earth coordinate



- Discretize the governing equation to the grid system

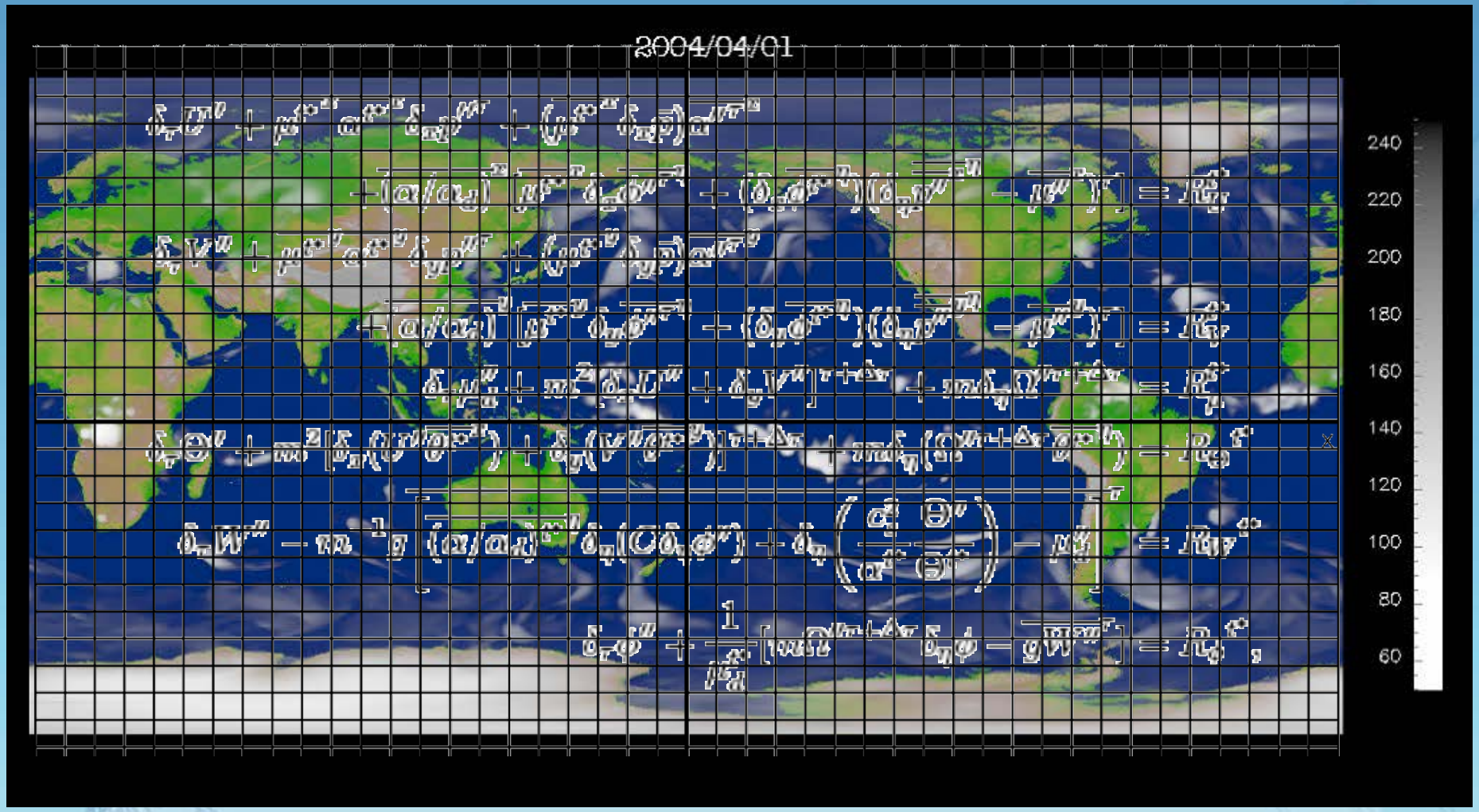


$$
\begin{aligned}
&\delta_\tau U'' + \overline{\mu^{t^\star}}^x \overline{\alpha^{t^\star}}^x \delta_x p'^{\prime\tau} + (\overline{\mu^{t^\star}}^x \delta_x \bar{p}) \overline{\alpha''^\tau}^x \\
&\qquad + \overline{(\alpha/\alpha_d)}^x [\overline{\mu^{t^\star}}^x \delta_x \overline{\phi''^\tau}^\eta + (\delta_x \overline{\phi^{t^\star}}^\eta)(\delta_\eta \overline{\overline{p''}^x}^\eta - \overline{\mu''}^x)^\tau] = R_U^{t^\star} \\
&\delta_\tau V'' + \overline{\mu^{t^\star}}^y \overline{\alpha^{t^\star}}^y \delta_y p'^{\prime\tau} + (\overline{\mu^{t^\star}}^y \delta_y \bar{p}) \overline{\alpha''^\tau}^y \\
&\qquad + \overline{(\alpha/\alpha_d)}^y [\overline{\mu^{t^\star}}^y \delta_y \overline{\phi''^\tau}^\eta + (\delta_y \overline{\phi^{t^\star}}^\eta)(\delta_\eta \overline{\overline{p''}^y}^\eta - \overline{\mu''}^y)^\tau] = R_V^{t^\star} \\
&\qquad \delta_\tau \mu_d'' + m^2 [\delta_x U'' + \delta_y V'']^{\tau+\Delta\tau} + m \delta_\eta \Omega''^{\tau+\Delta\tau} = R_\mu^{t^\star} \\
&\delta_\tau \Theta'' + m^2 [\delta_x (U'' \overline{\theta^{t^\star}}^x) + \delta_y (V'' \overline{\theta^{t^\star}}^y)]^{\tau+\Delta\tau} + m \delta_\eta (\Omega''^{\tau+\Delta\tau} \overline{\theta^{t^\star}}^\eta) = R_\Theta{}^{t^\star} \\
&\delta_\tau W'' - m^{-1} g \overline{\left[ \overline{(\alpha/\alpha_d)^{t^\star}}^\eta \delta_\eta (C \delta_\eta \phi'') + \delta_\eta \left( \frac{c_s^2}{\alpha^{t^\star}} \frac{\Theta''}{\Theta^{t^\star}} \right) - \mu_d'' \right]}^\tau = R_W{}^{t^\star} \\
&\qquad \delta_\tau \phi'' + \frac{1}{\mu_d^{t^\star}} [m \Omega''^{\tau+\Delta\tau} \delta_\eta \phi - \overline{g W''^\tau}] = R_\phi{}^{t^\star},
\end{aligned}
$$

$$
\begin{aligned}
R_U^{t^\star} &= -(\overline{\mu_d}^x \overline{\alpha}^x \delta_x p' - \overline{\mu_d}^x \overline{\alpha'}^x \delta_x \bar{p}) - \overline{(\alpha/\alpha_d)}^x (\overline{\mu_d}^x \delta_x \overline{\phi'}^\eta - \delta_\eta \overline{\overline{p'}^x}^\eta \delta_x \overline{\phi}^\eta + \overline{\mu_d'}^x \delta_x \overline{\phi}^\eta) \\
&\quad + F_{U_{cor}} + \text{advection} + \text{mixing} + \text{physics} \\
R_V^{t^\star} &= -(\overline{\mu_d}^y \overline{\alpha}^y \delta_y p' - \overline{\mu_d}^y \overline{\alpha'}^y \delta_y \bar{p}) - \overline{(\alpha/\alpha_d)}^y (\overline{\mu_d}^y \delta_y \overline{\phi'}^\eta - \delta_\eta \overline{\overline{p'}^y}^\eta \delta_y \overline{\phi}^\eta + \overline{\mu_d'}^y \delta_y \overline{\phi}^\eta) \\
&\quad + F_{V_{cor}} + \text{advection} + \text{mixing} + \text{physics} \\
R_W^{t^\star} &= m^{-1} g \overline{(\alpha/\alpha_d)}^\eta [\delta_\eta p' + \bar{\mu}_d \overline{q_m}^\eta] - m^{-1} \mu_d' g \\
&\quad + F_{W_{cor}} + \text{advection} + \text{mixing} + \text{buoyancy} + \text{physics}.
\end{aligned}
$$

**Numerical weather prediction (NWP)**

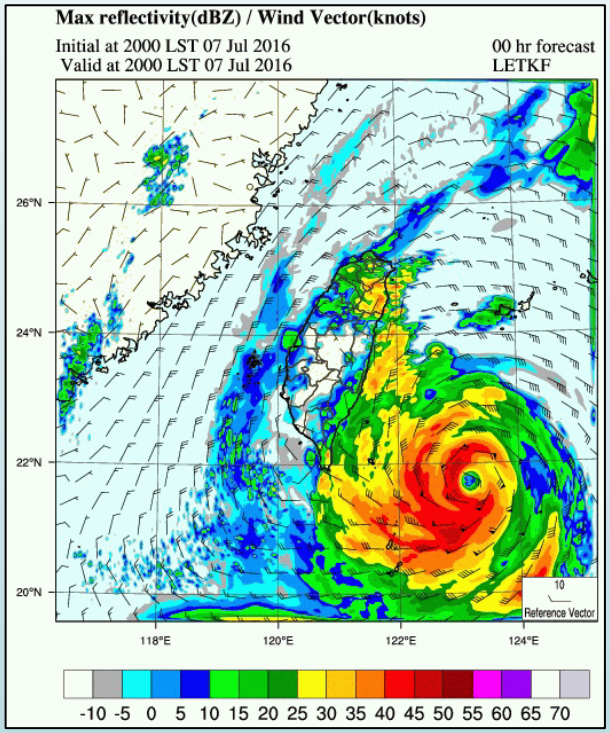
**→ The numerical solution of the fluid dynamic equations**



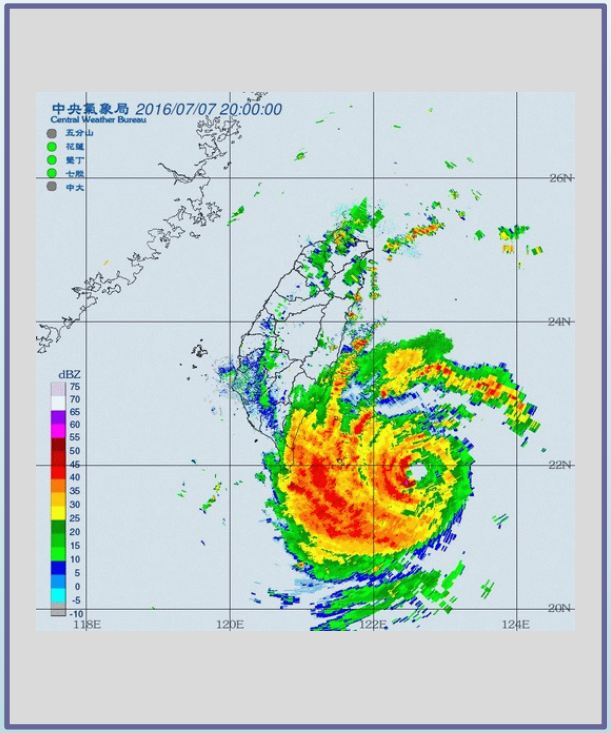

Is it a real atmosphere ?

**NWP need the knowledge among math, physics, computer science, statistics…**

# Sometimes miracle happened




Model forecast

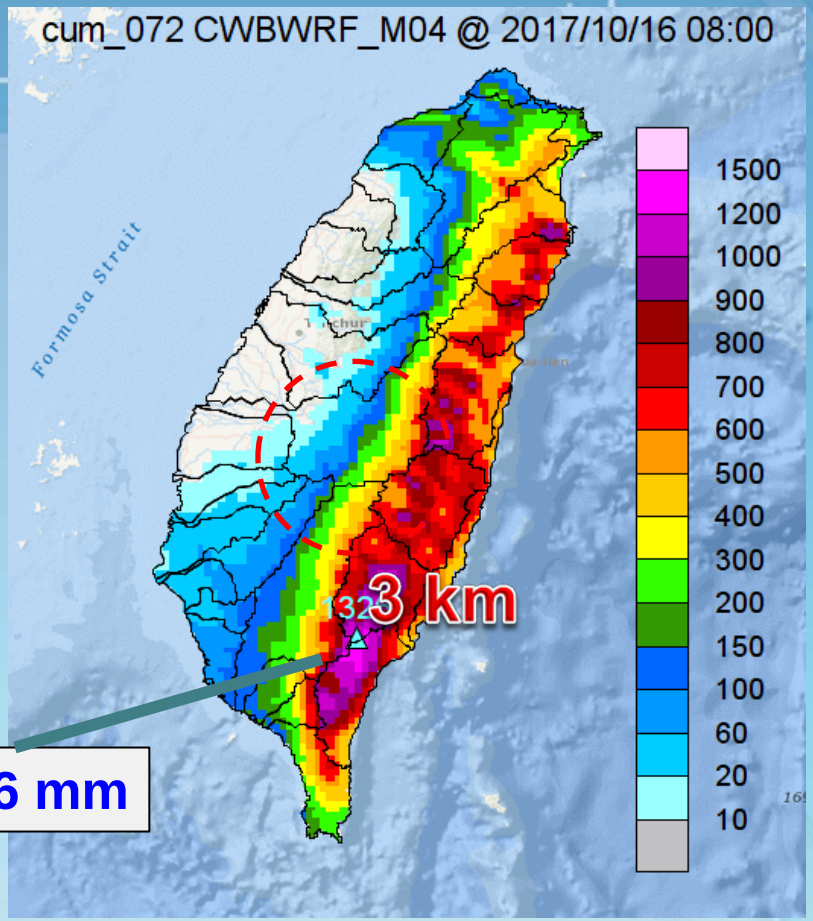



Radar observation

Almost reproduce the “Typhoon” in the MODEL

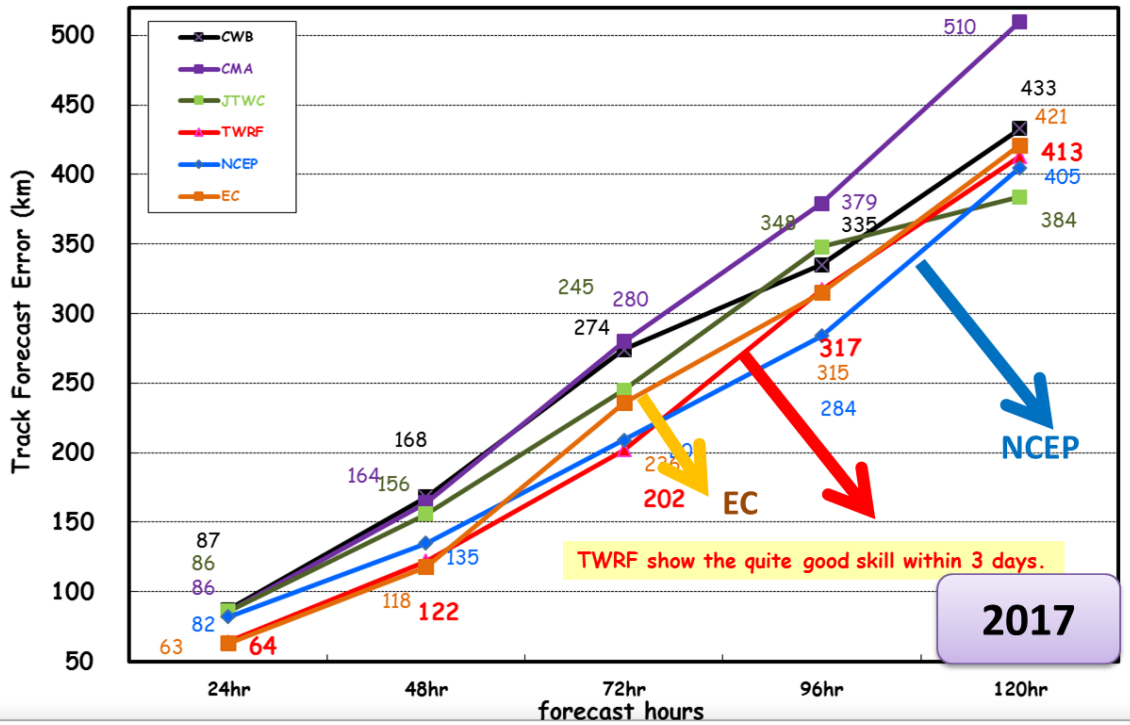
# Initial at 2017101600 UTC

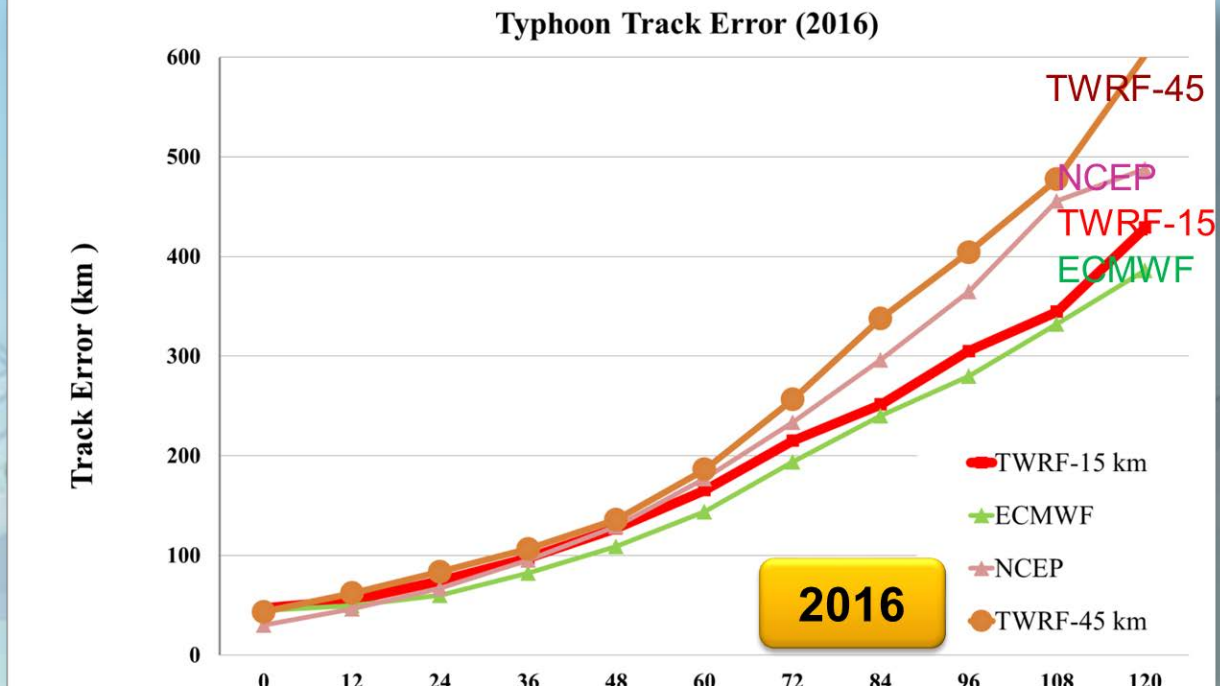



## Typhoon Khanun related distant rainfall

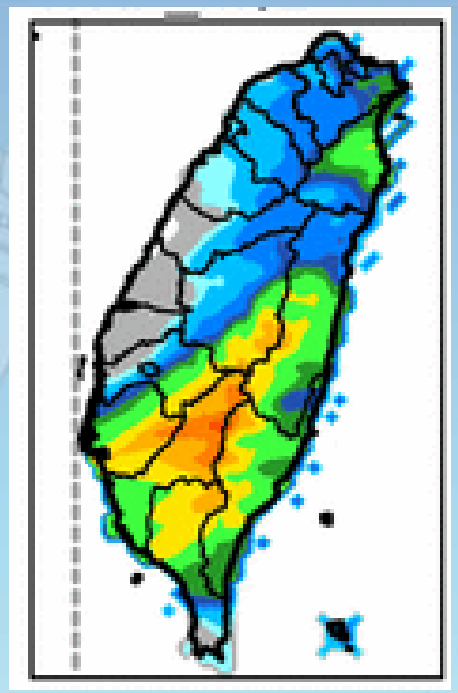
3-day accumulated rainfall ( 多采公司繪圖 )


CWB
CMA
JTWC
TWRF
NCEP
EC
Track Forecast Error (km)
forecast hours
24hr
48hr
72hr
96hr
120hr
510
433
421
413
405
384
379
348
335
280
245
274
317
315
284
168
164
156
135
118
122
87
86
86
82
63
64
202
EC
NCEP
TWRF show the quite good skill within 3 days.
2017

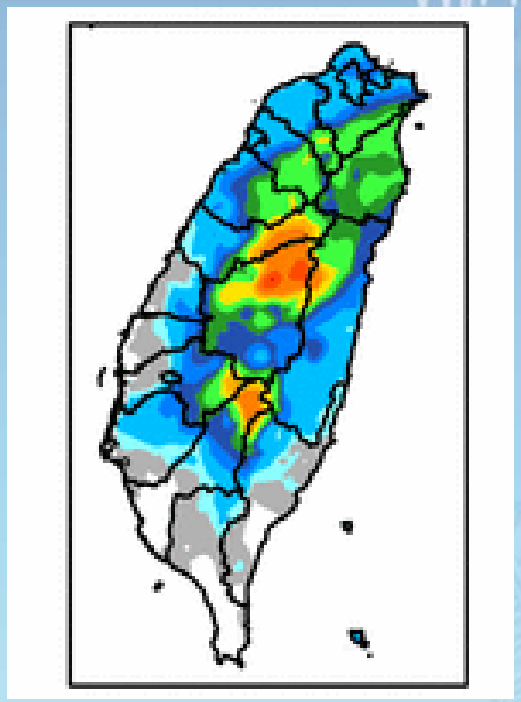

Typhoon Track Error (2016)
Track Error (km )
TWRF-45
NCEP
TWRF-15
ECMWF
TWRF-15 km
ECMWF
NCEP
TWRF-45 km
2016

# However

Does the model performs so Perfect all the time?

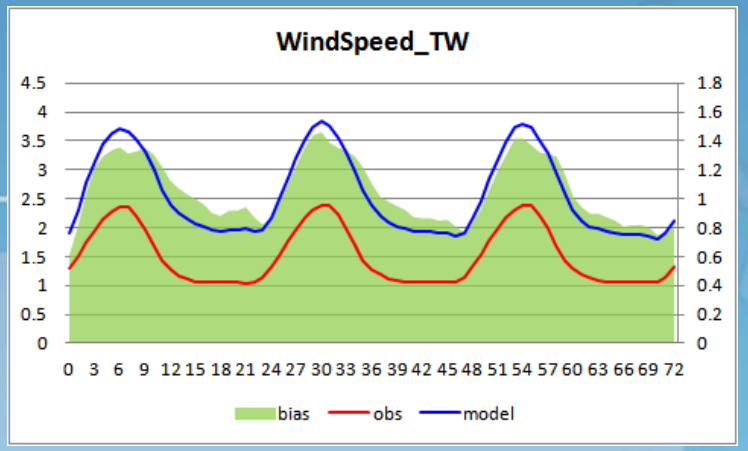


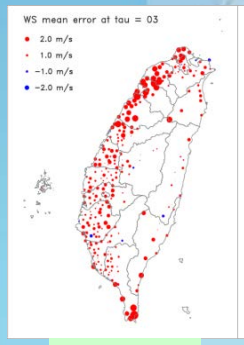
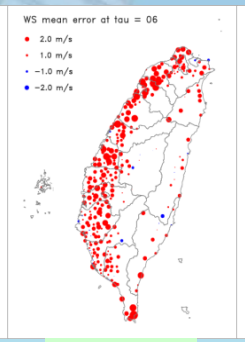
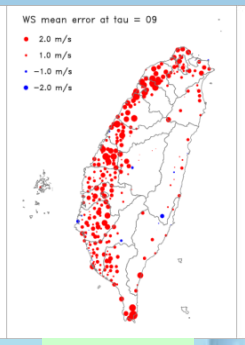
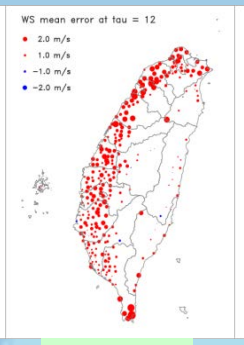
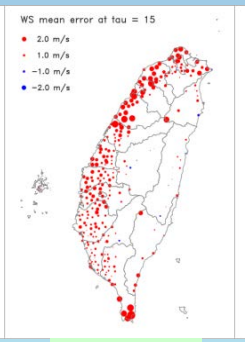
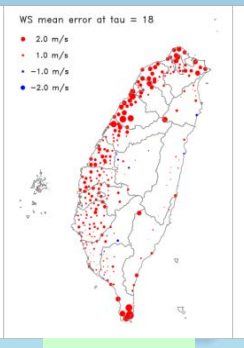
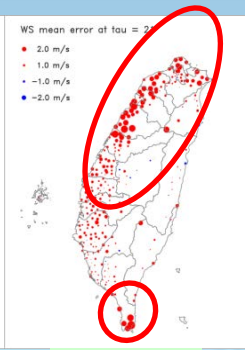
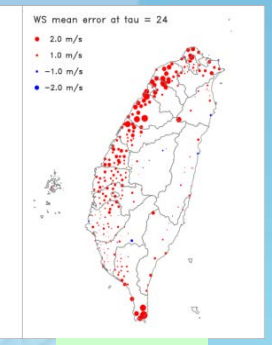
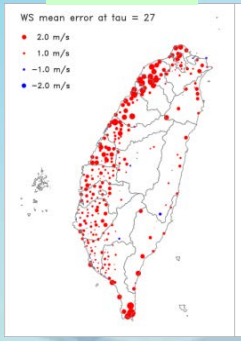
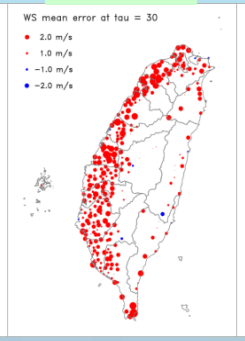
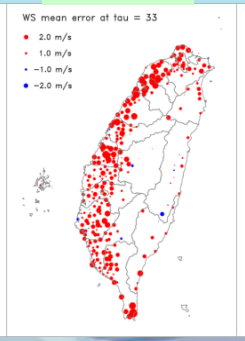
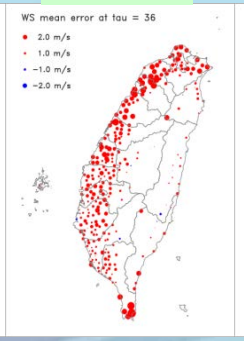
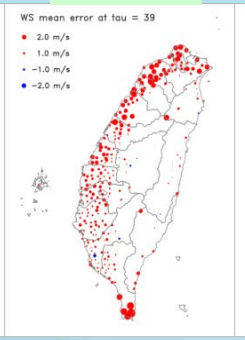
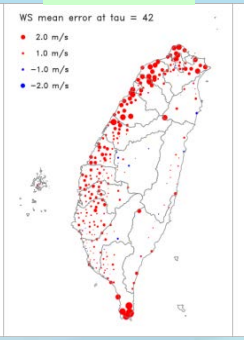
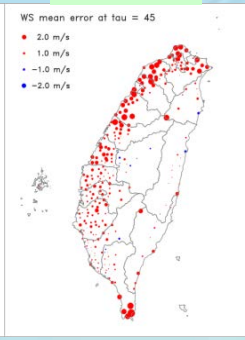
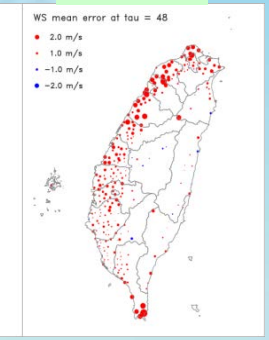
Model

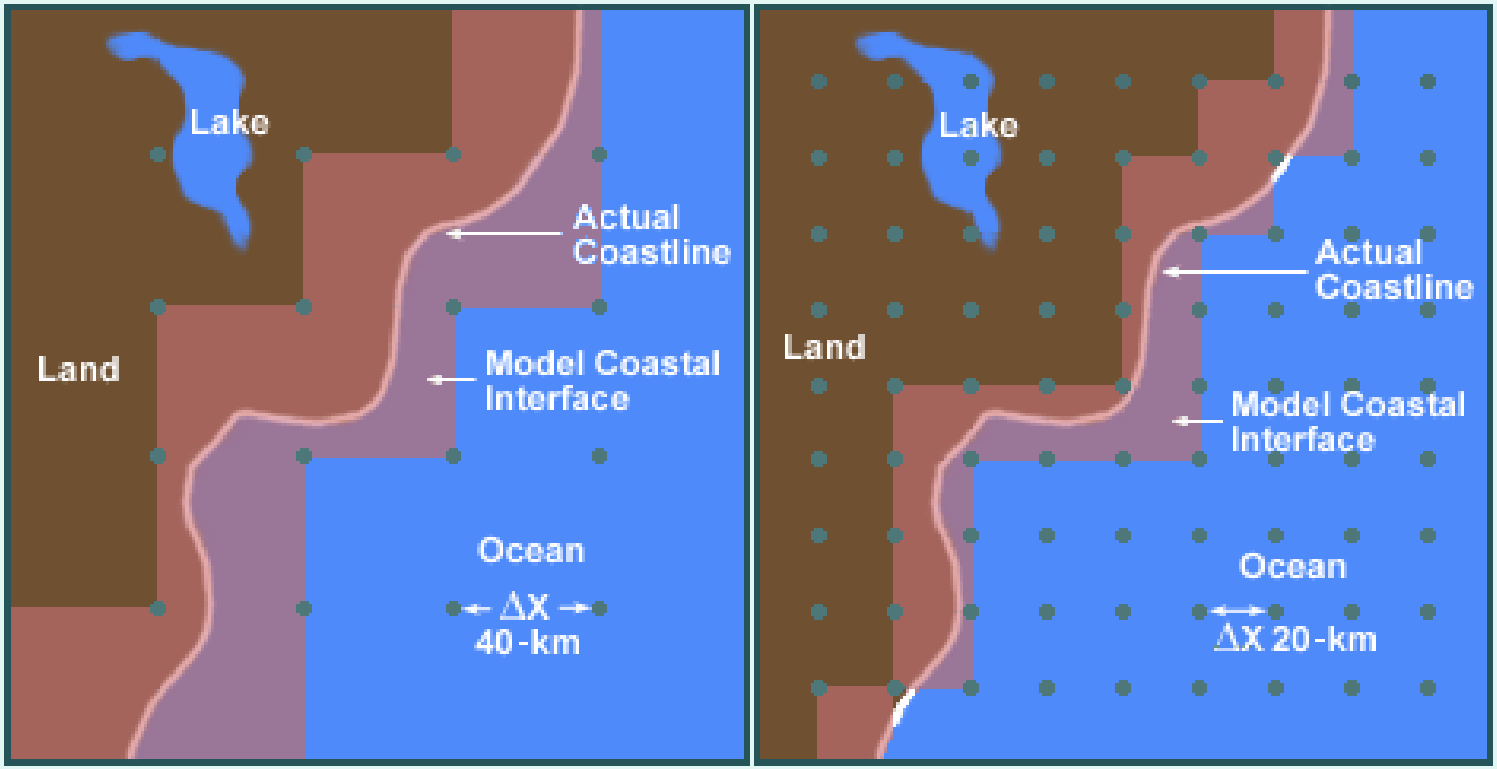


OBS

# Wind speed prediction error




| 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |
| 11 LST | 14 LST | 17 LST | 20 LST | 23 LST | 02 LST | 05 LST | 08 LST |
|  |  |  |  |  |  |  |  |
| 27 | 30 | 33 | 36 | 39 | 42 | 45 | 48 |

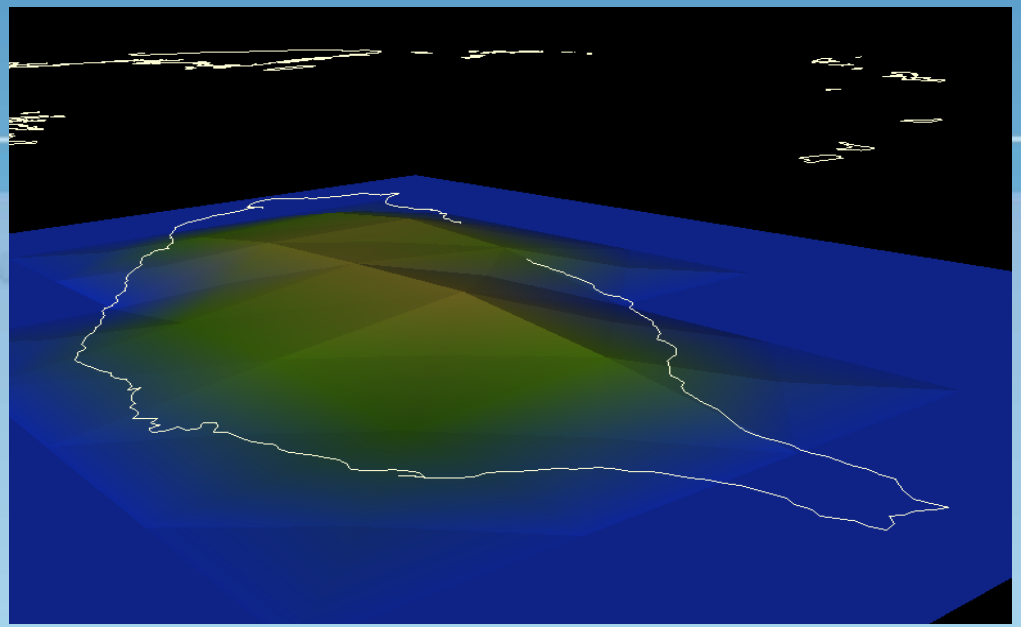



Model A: 40-km Resolution

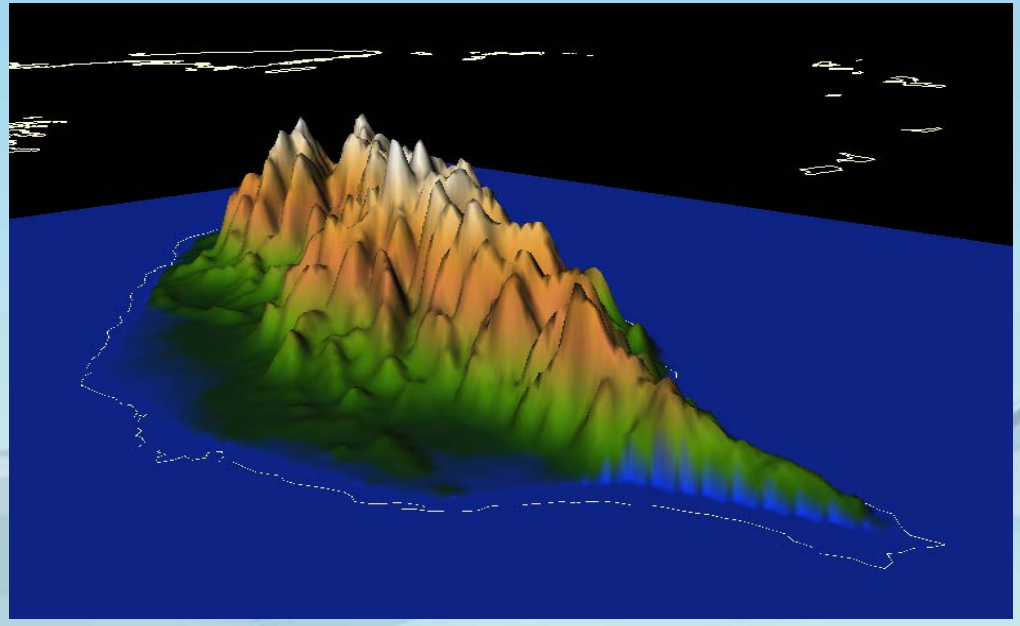
Model B: 20-km Resolution

Coastal Region within the Model

The COMET Program

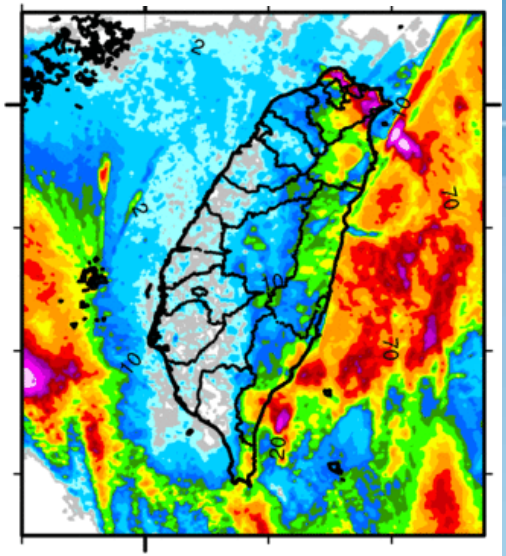


15-km resolution

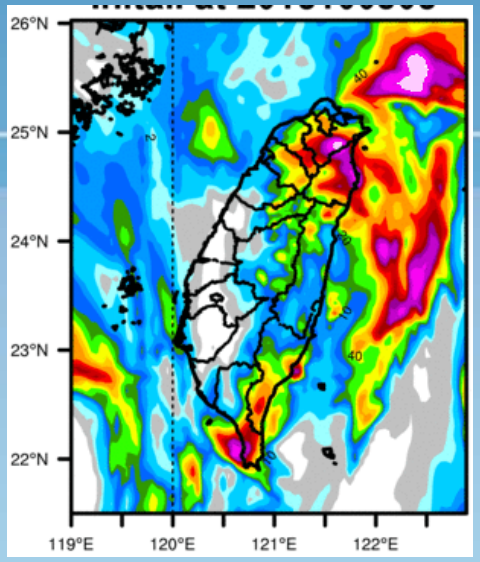


5-km resolution

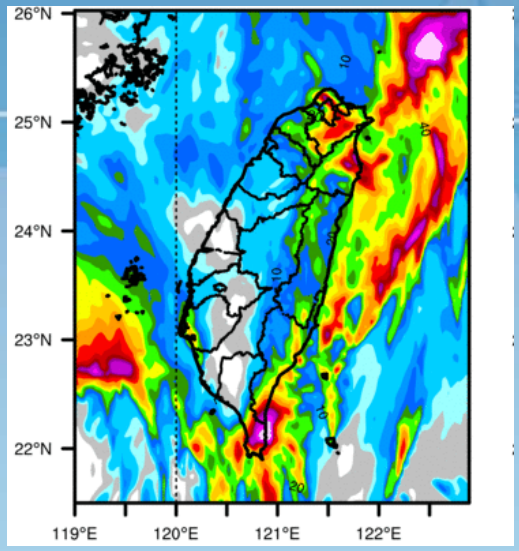
Observation



5 km

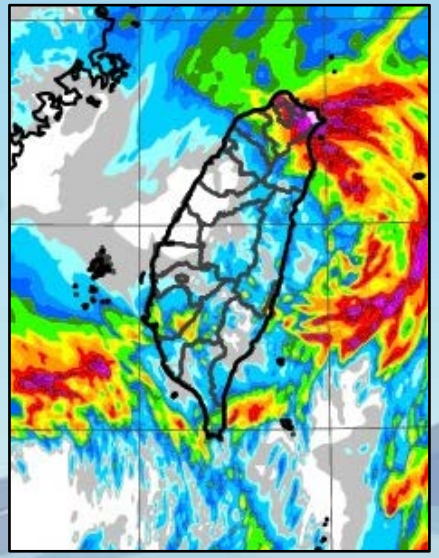



3 km

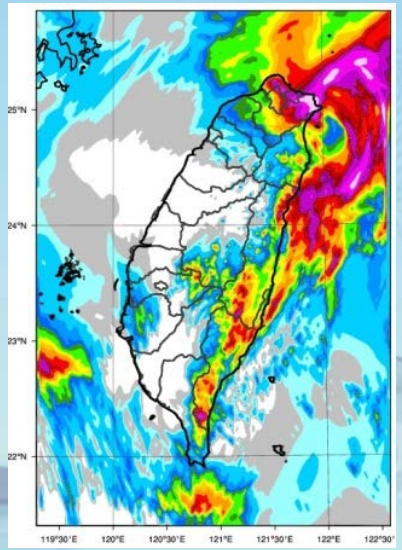


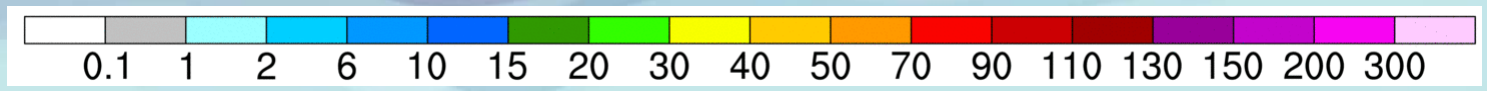

20161009 case

2 km



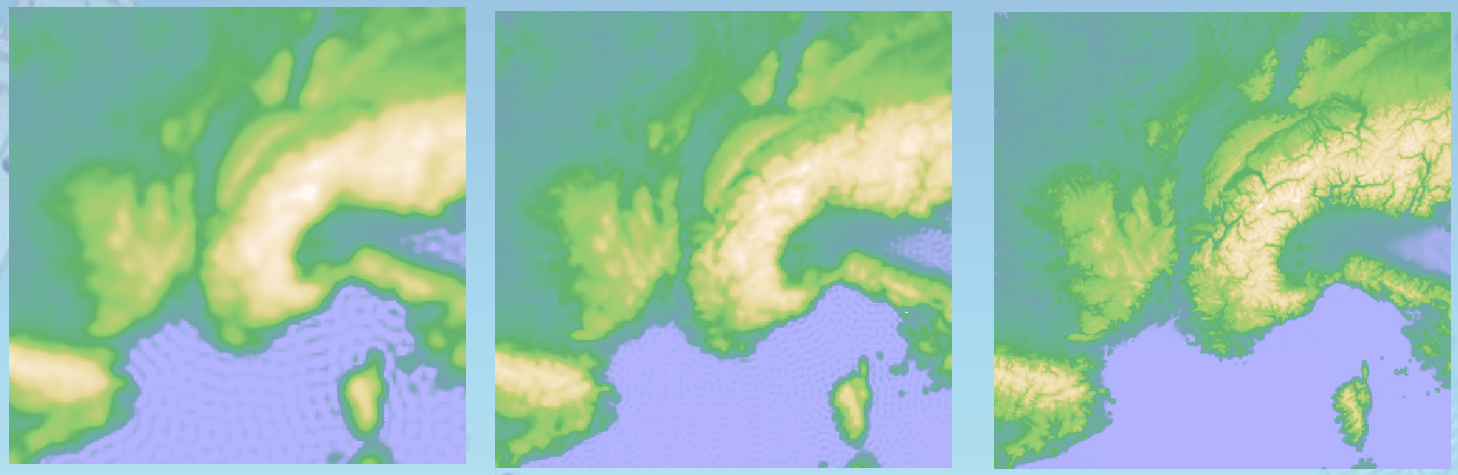
1 km



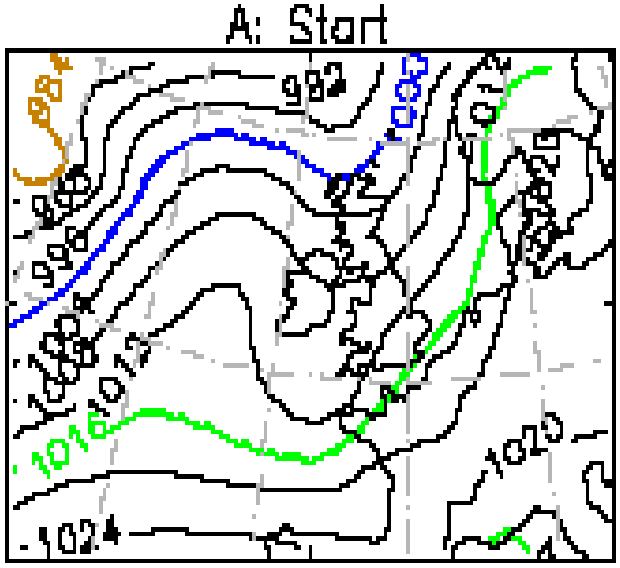


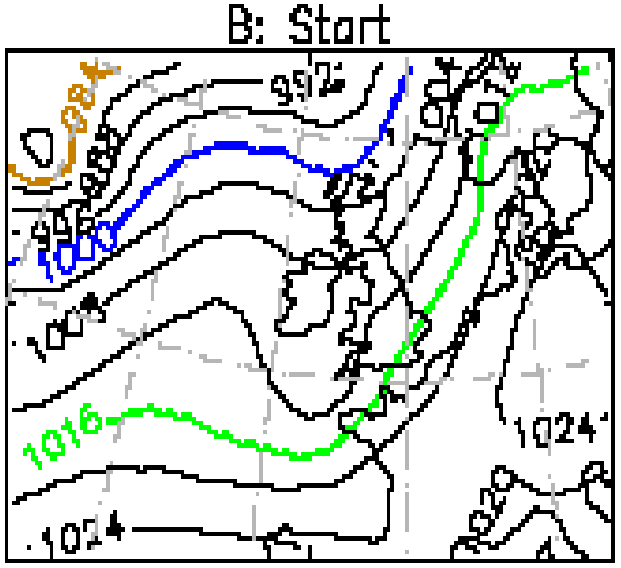
- **The more details in the model, the better results.**
- **It means we need much more computer power**

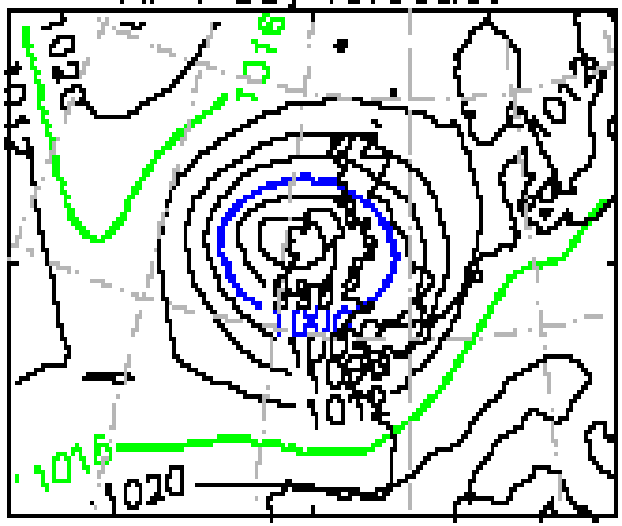
(A) 10 km resolution , (B) 5 km resolution , (C) 1.25 km resolution.

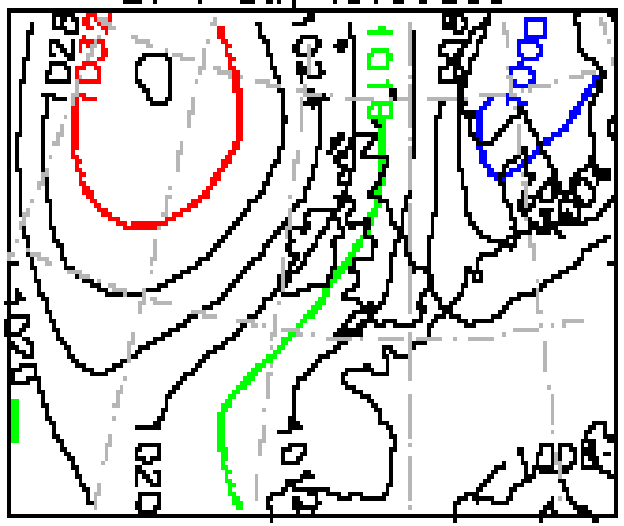


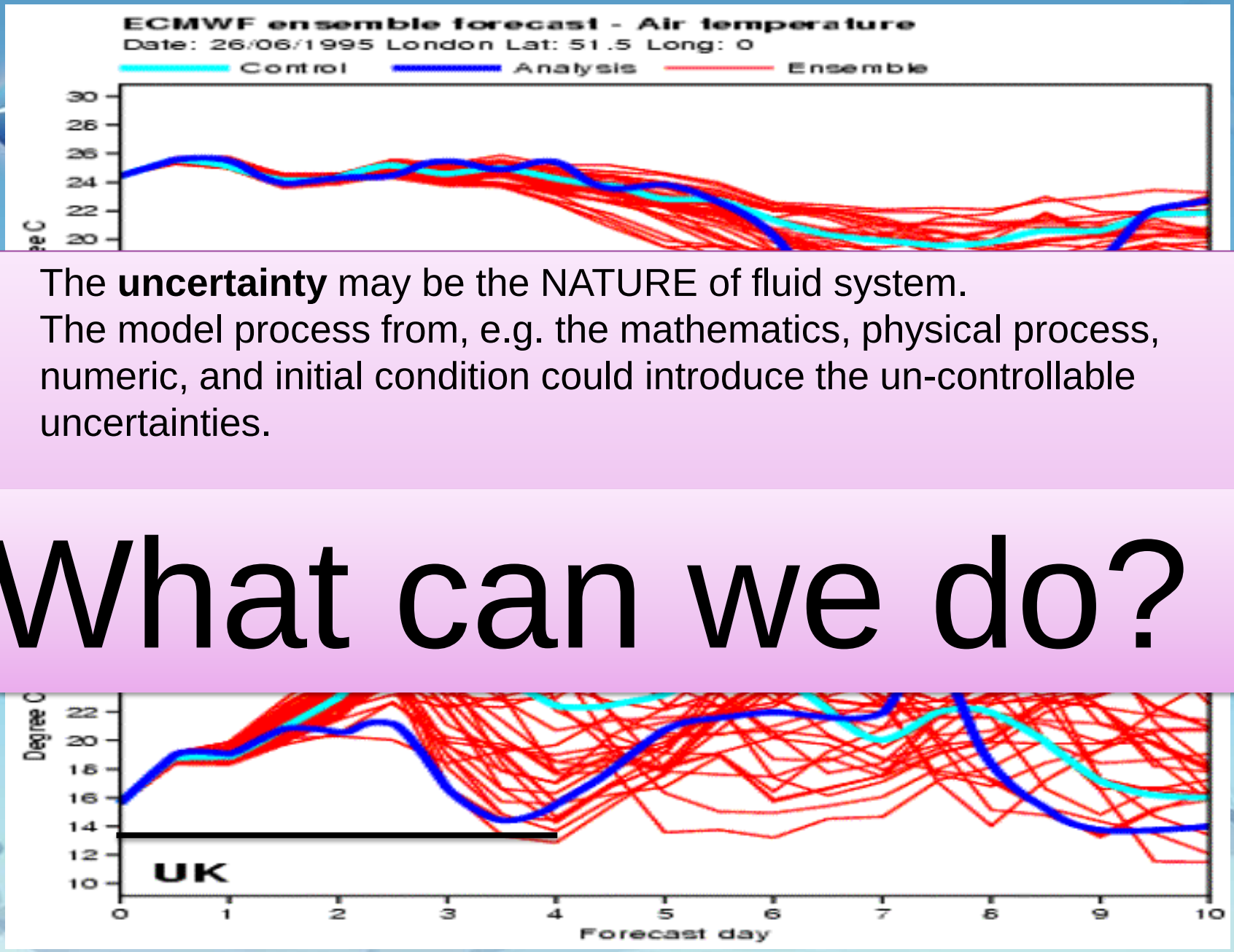
| Resolution | 1 | 2 | 8 |
|---|---|---|---|
| Computing cost | 1 | 8 | 512 |


A: Start
984
988
992
996
1000
1004
1008
1012
1016
1020
1024


B: Start
984
988
992
996
1000
1004
1008
1012
1016
1020
1024


A: 4 day forecast
1000
1004
1008
1012
1016
1020

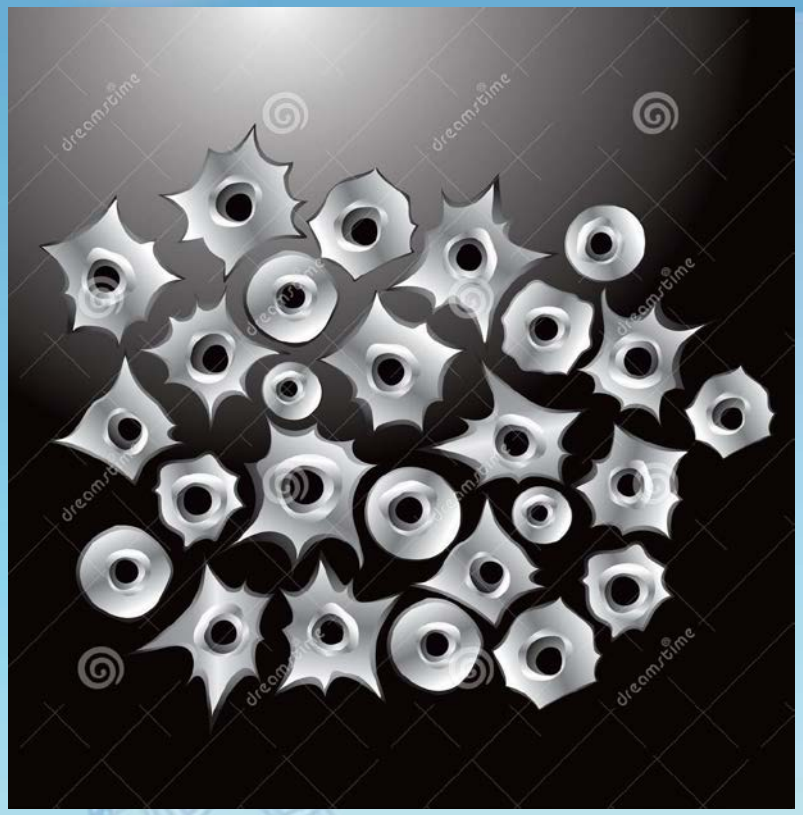

B: 4 day forecast
1000
1004
1008
1012
1016
1020
1024
1028
1032




- The **uncertainty** may be the NATURE of fluid system.
- The model process from, e.g. the mathematics, physical process, numeric, and initial condition could introduce the un-controllable uncertainties.

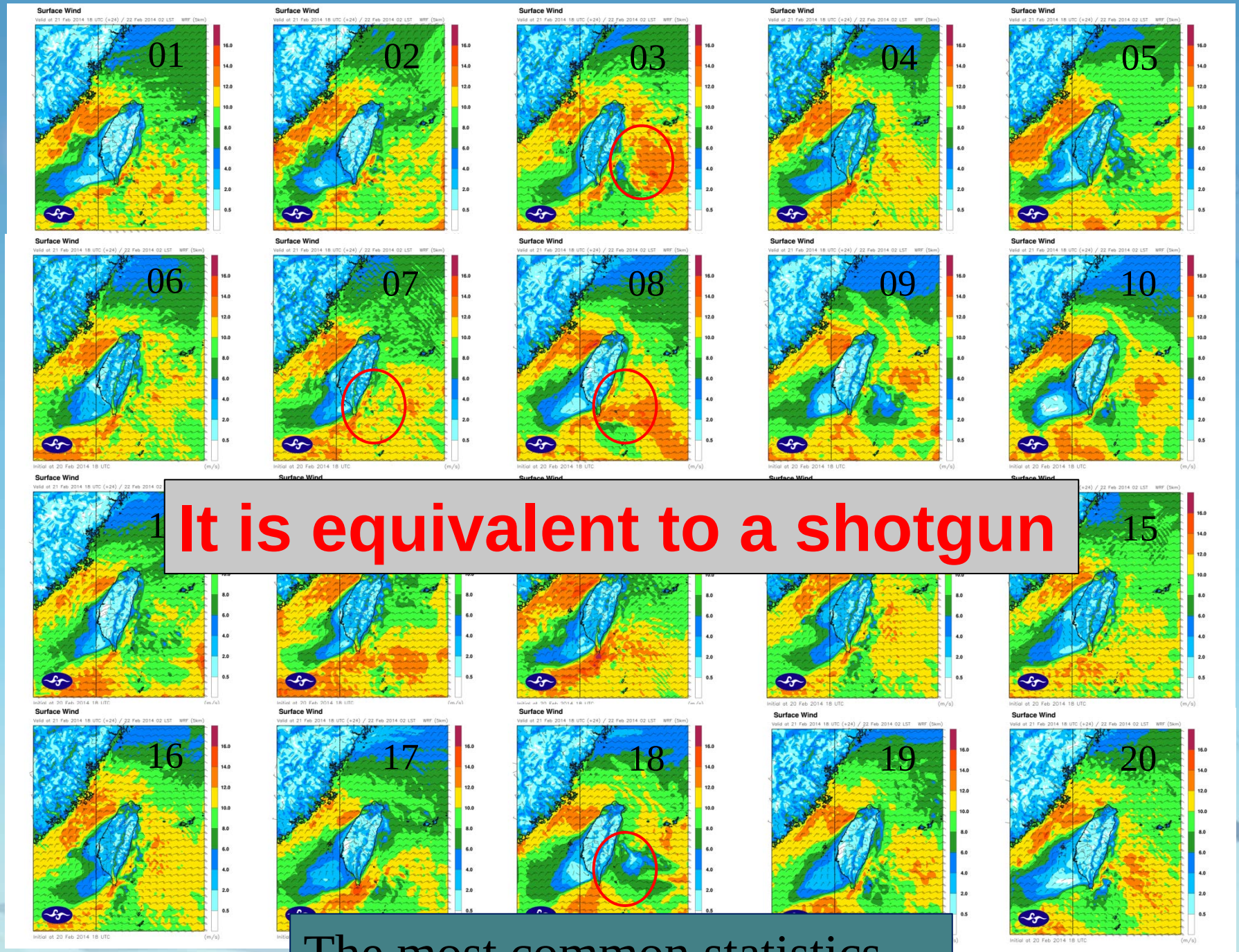
# What can we do?

**A single (deterministic) model behaves like a sniper rifle**



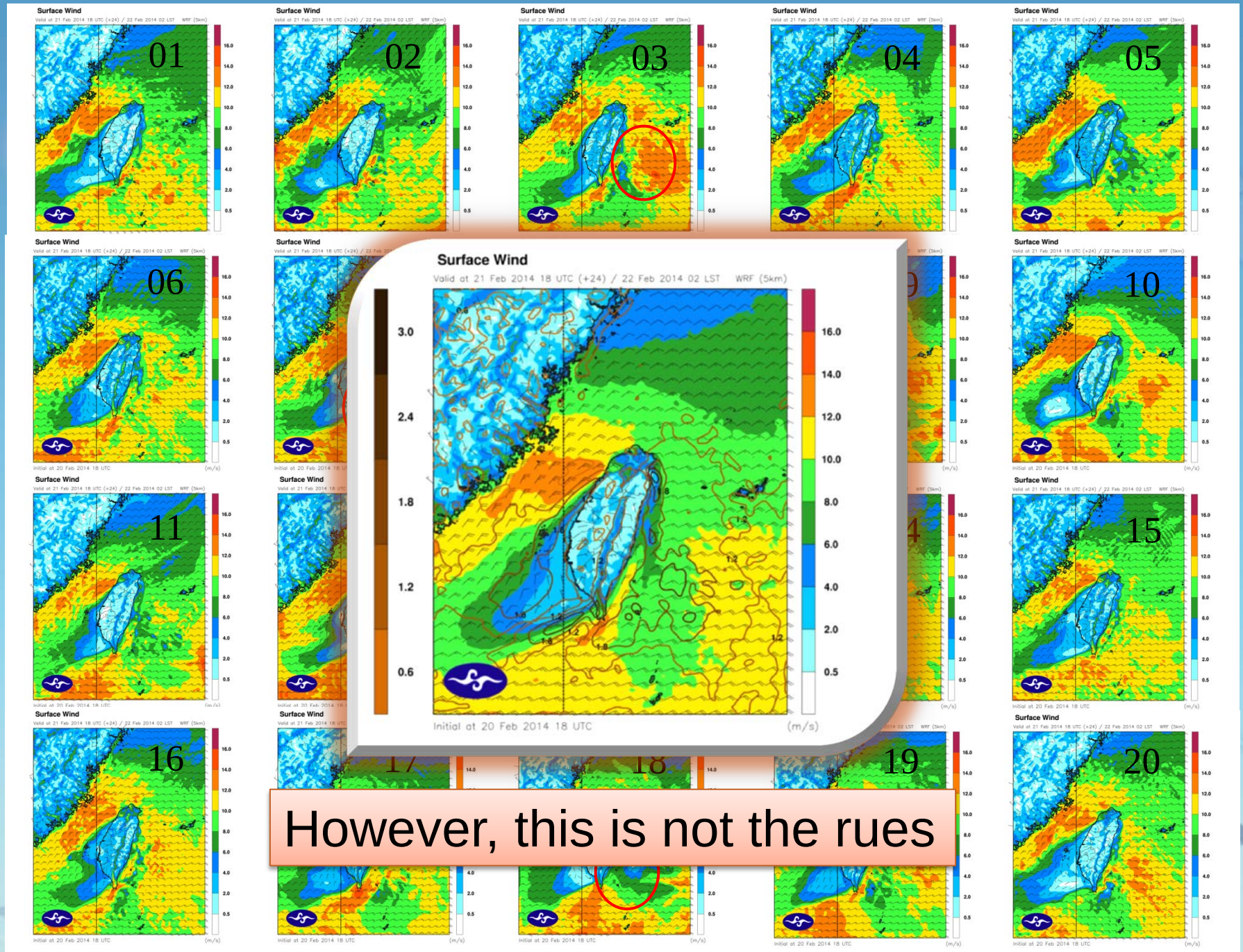
**How about a shotgun?**

**Toward to the ensemble forecast**
**（系集預報）**

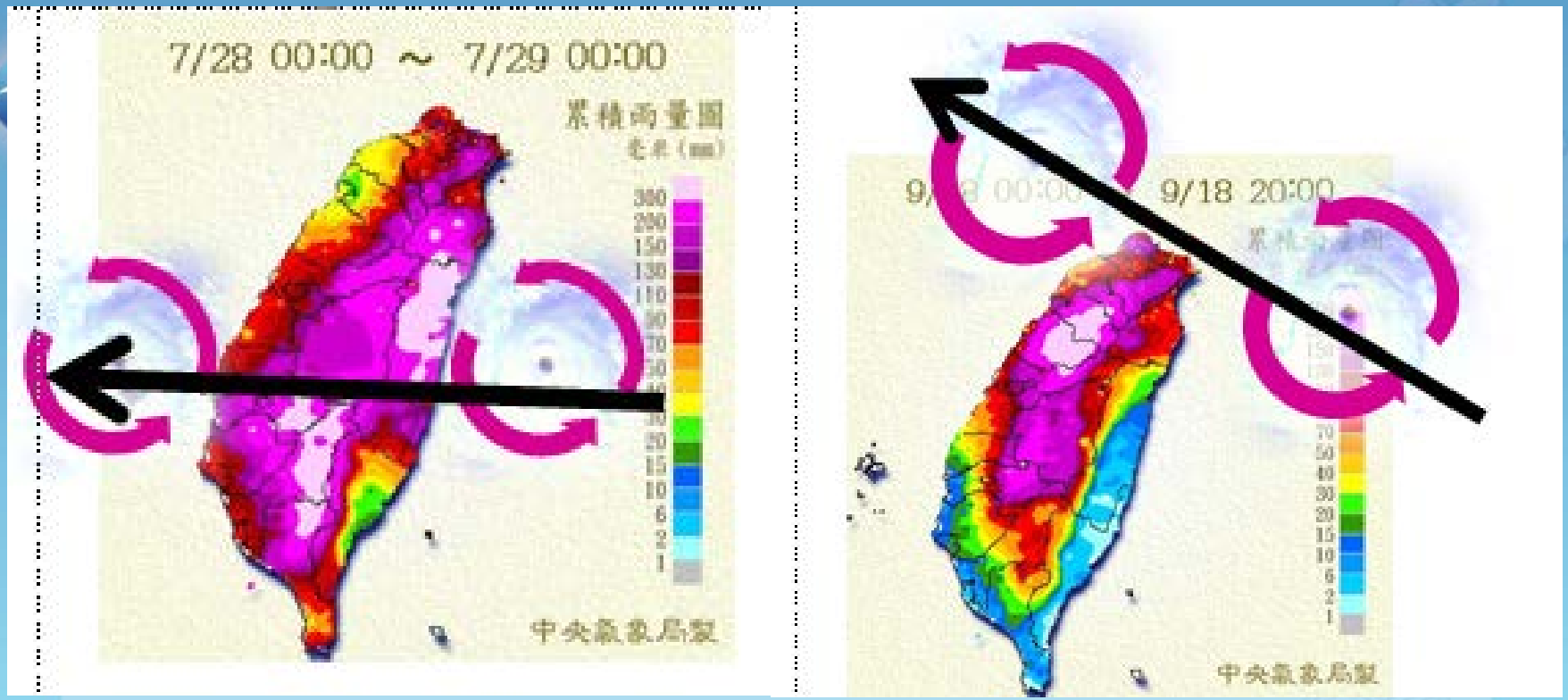



**It is equivalent to a shotgun**

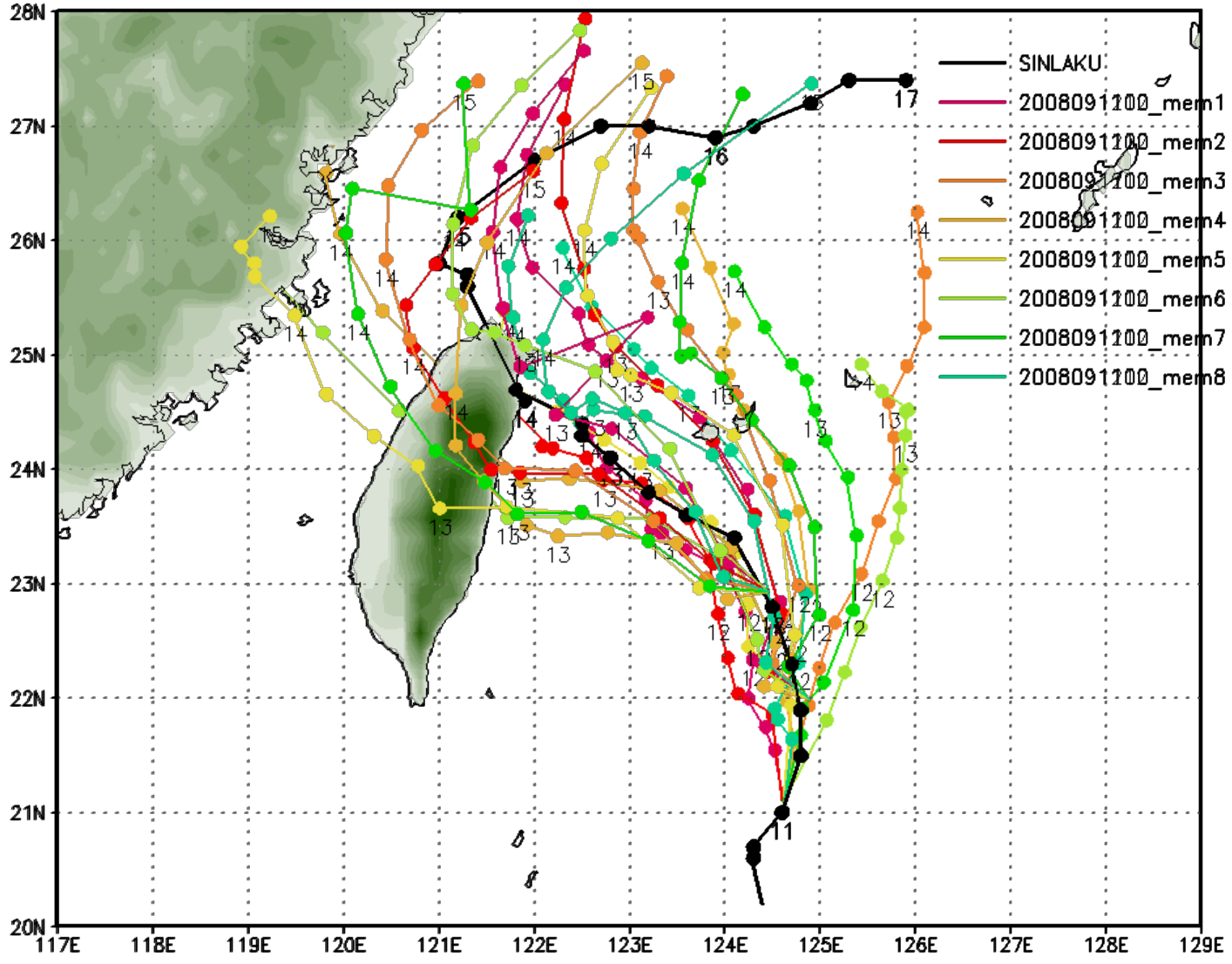
The most common statistics…



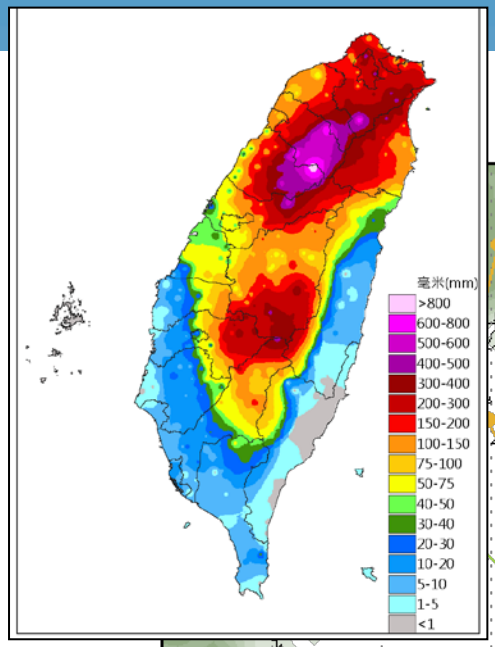

However, this is not the rues

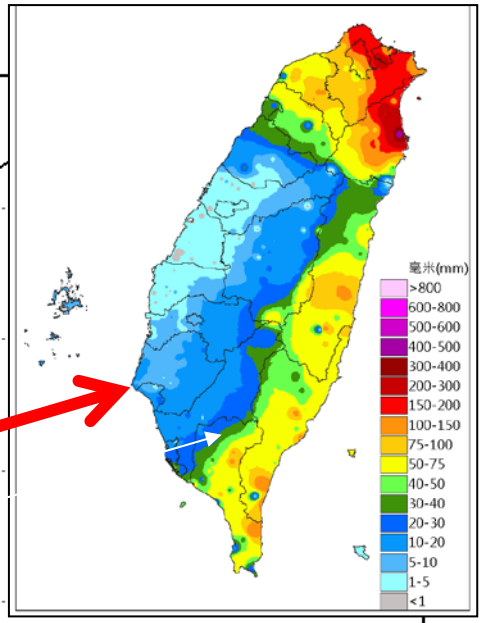


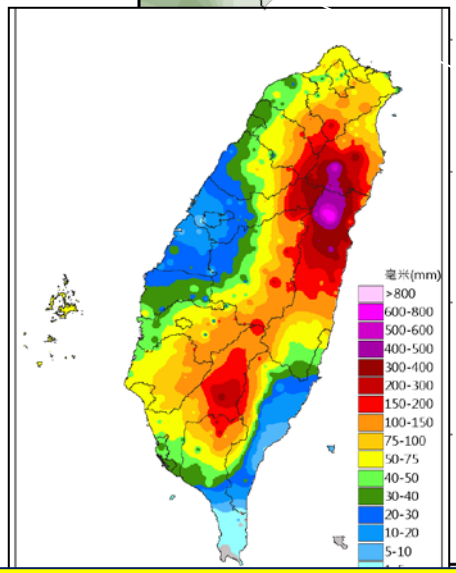

# Terrain locking effect




What can we do to extract the useful model TY QPF information from ensemble forecast?



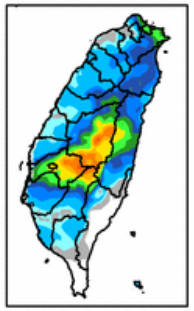






Take the ensemble mean? Weighted over the members?
“Mean” is not always a good idea

# Application of the probability products

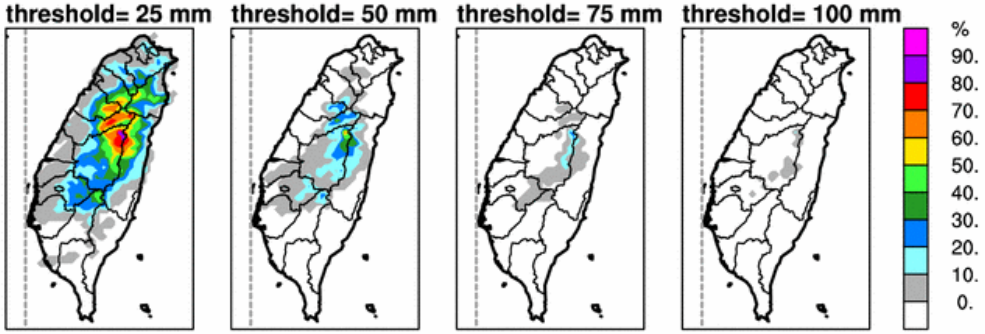
OBS



initail at 0000 UTC 05 May 2014

12~24hr fcst Accumulated rainfall from 2014050512 ~ 2014050600

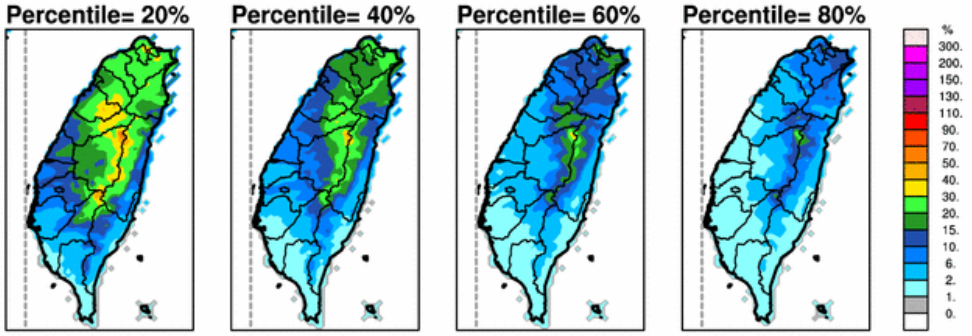
## Probability exceeding rainfall threshold




initail at 0000 UTC 06 May 2014

00~12hr fcst Accumulated rainfall from 2014050600 ~ 2014050612

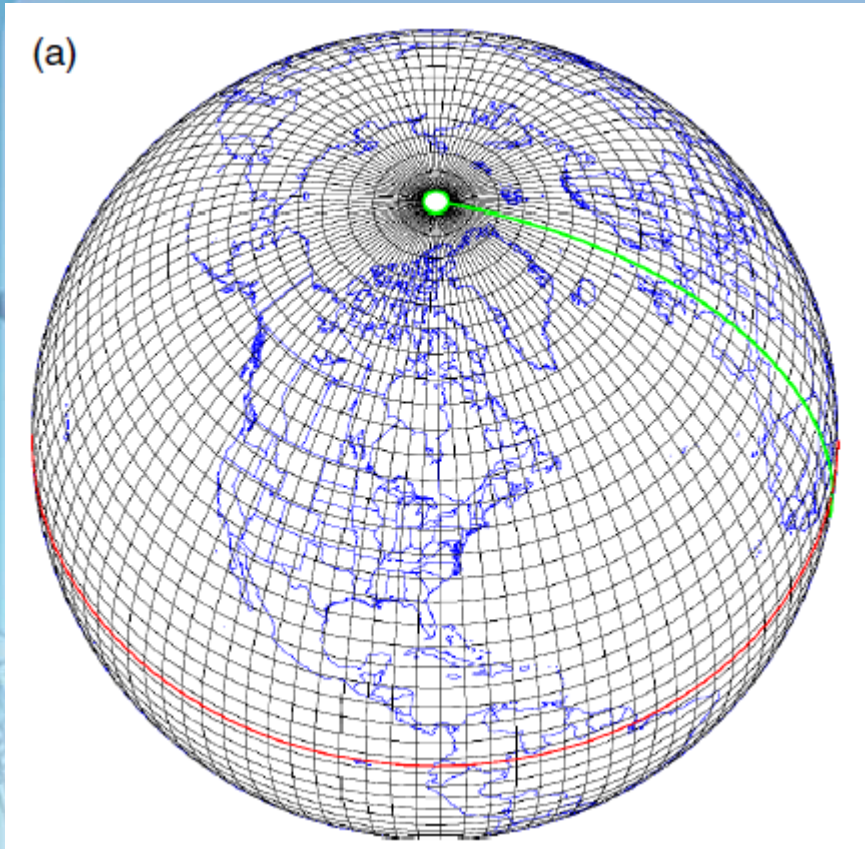
## QPF exceeding probability threshold



**因應對策：**

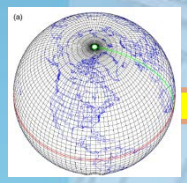
- **引進大數據分析技術，提高負載/再生能源預測準確度**
- **日前預測分析技術：**
  **未來七天 (For Day-Ahead SCUC、SCED、Ancillary Service)**
- **即時預測分析技術：**
  **未來3~4小時(For Real-Time SCED、Ancillary Service)**
  **每5或15分鐘(For Real-Time Regulation & Spinning Reserve)**

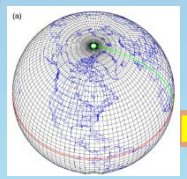
台電調度處吳副處長

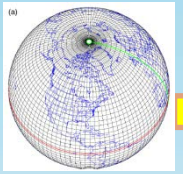


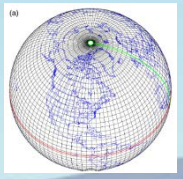

- ~25 km horizontal resolution
- Updated 4 times per day
- 6-Hourly output, extended to 14 days

00Z 06Z 12Z 18Z 00Z 06Z 12Z 18Z



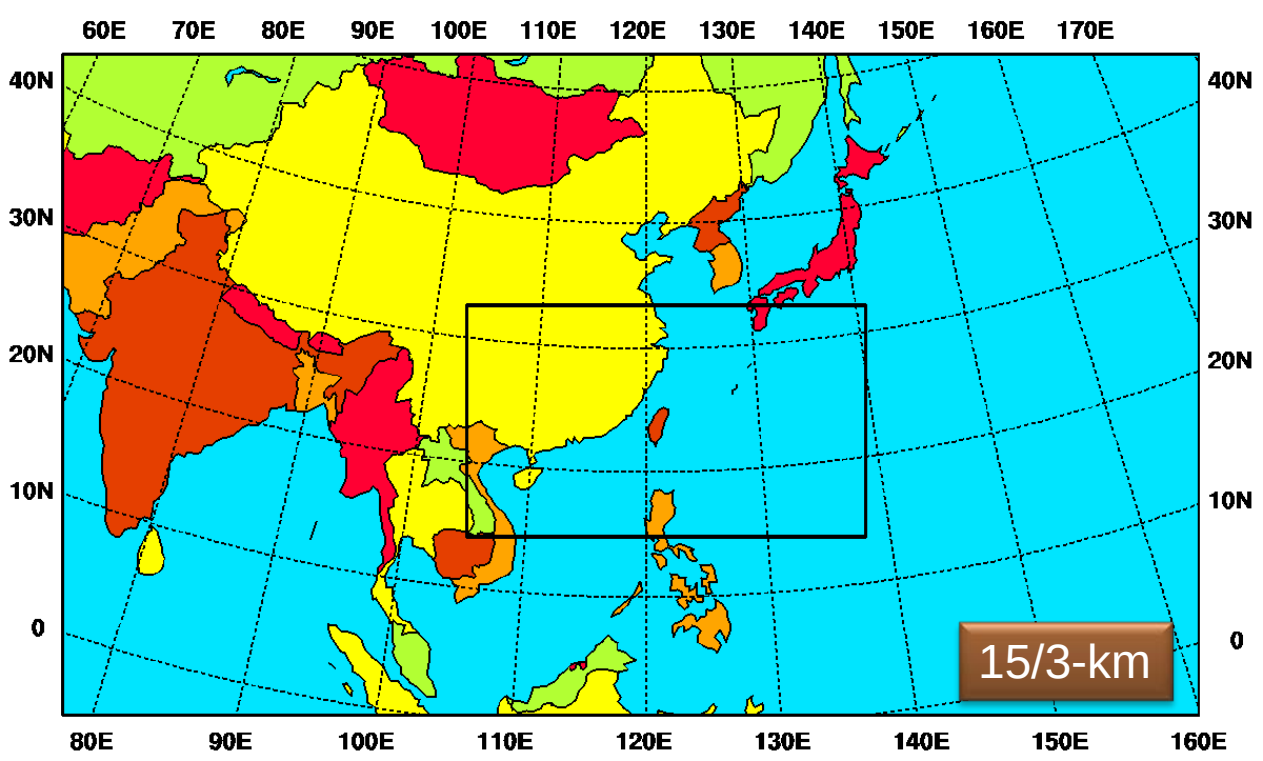






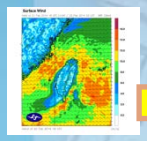
6-hr output frequency to 14 days

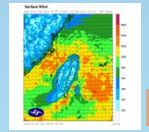
# Deterministic model system

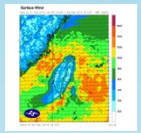


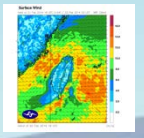

- 15/3 km horizontal resolution
- Updated 4 times per day
- Hourly output, extended to 84 hour

00Z 06Z 12Z 18Z 00Z 06Z 12Z 18Z



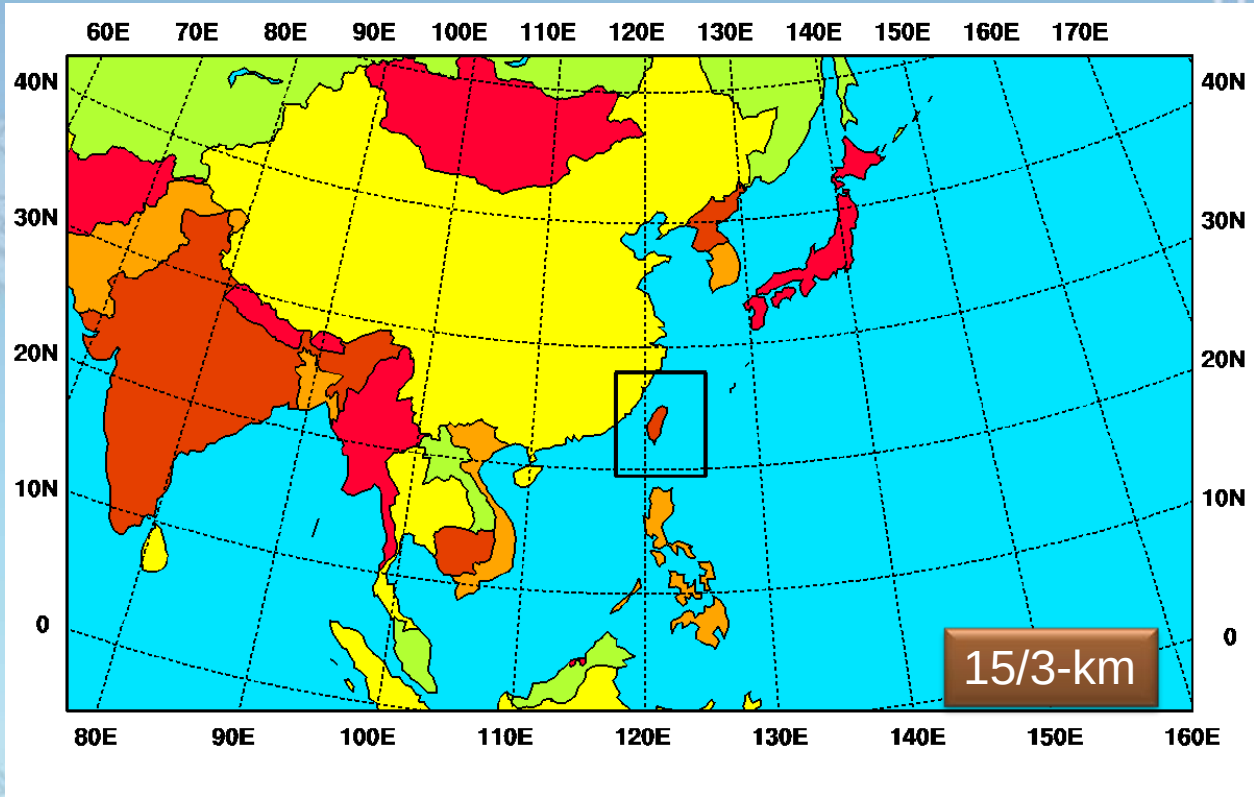




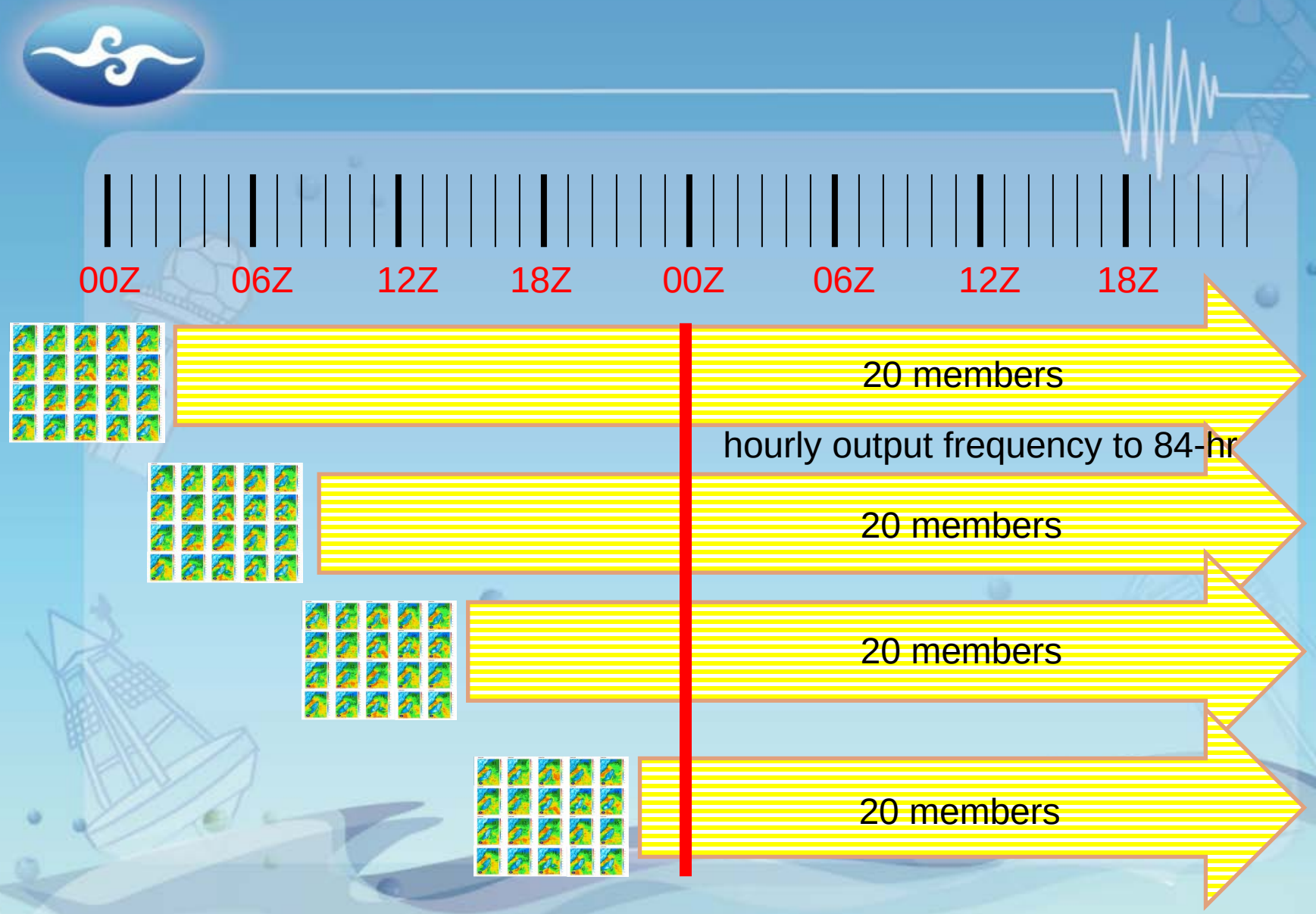


hourly output frequency to 84-hr

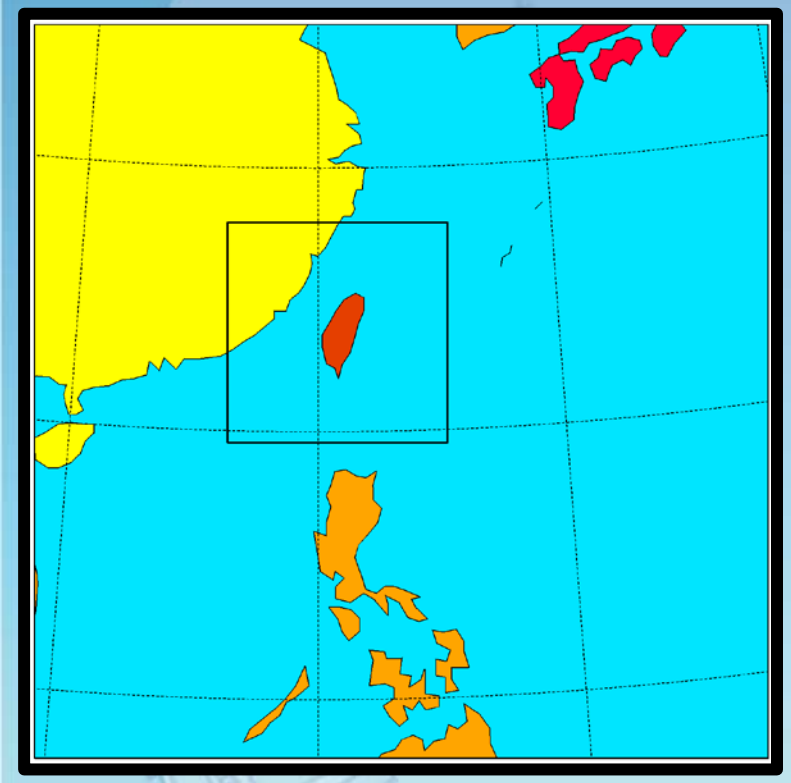
# Ensemble model system



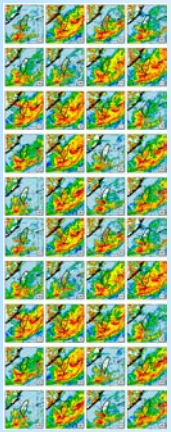

- 15/3 km horizontal resolution
- Updated 4 times per day, **20 members per run**
- Hourly output, extended to 84 hour


00Z
06Z
12Z
18Z
00Z
06Z
12Z
18Z
20 members
hourly output frequency to 84-hr
20 members
20 members
20 members

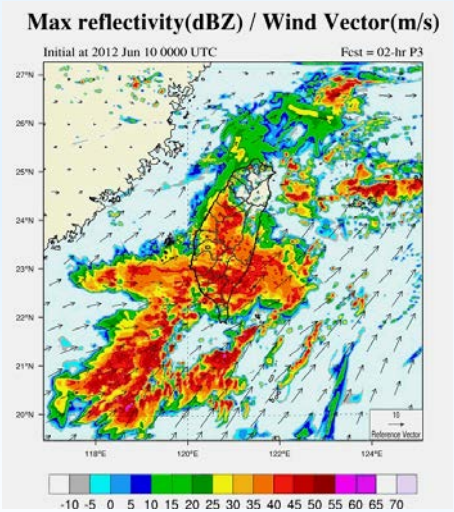
# Convective scale nowcasting



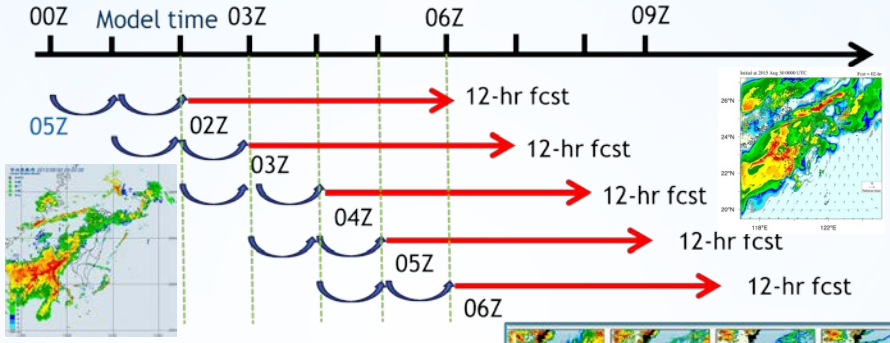
- 10-km/2-km Domain
  - Convective scale DA, assimilate the Taiwan local observations, especially for the radar oservation
  - hourly updated (24 times per day)
  - Hourly output, extended to 12-hr forecast



Hybrid 3DEnVAR



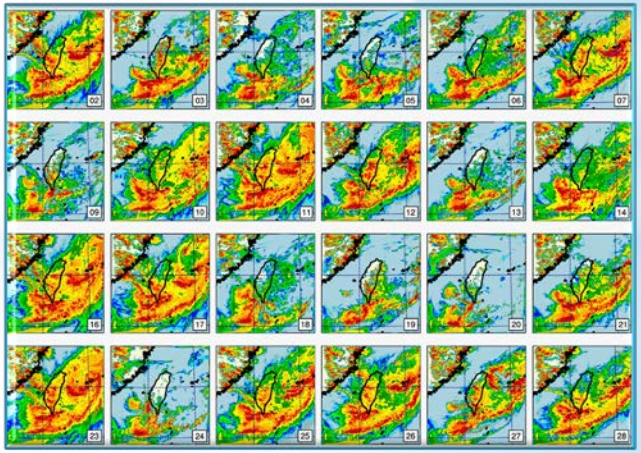

LETKF
In 2017




Realtime, hourly updated system extended to 24-hr forecast

Radar and all available observations

Convective scale EPS

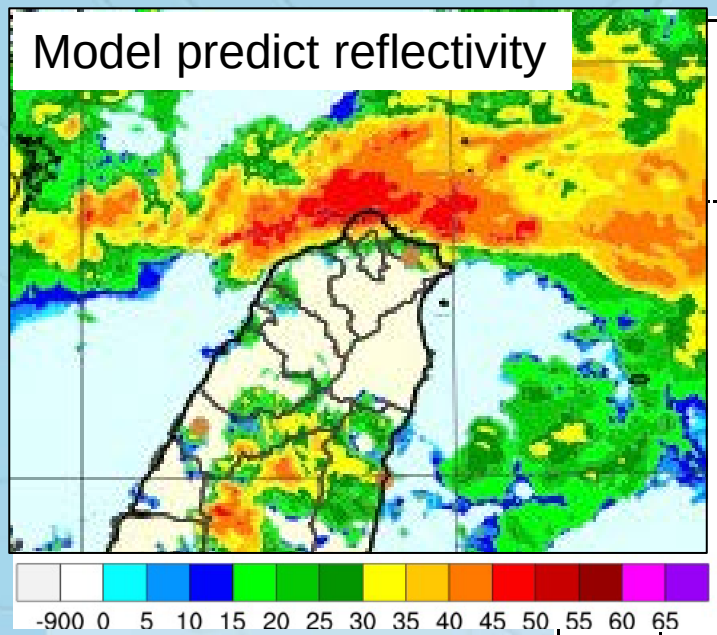


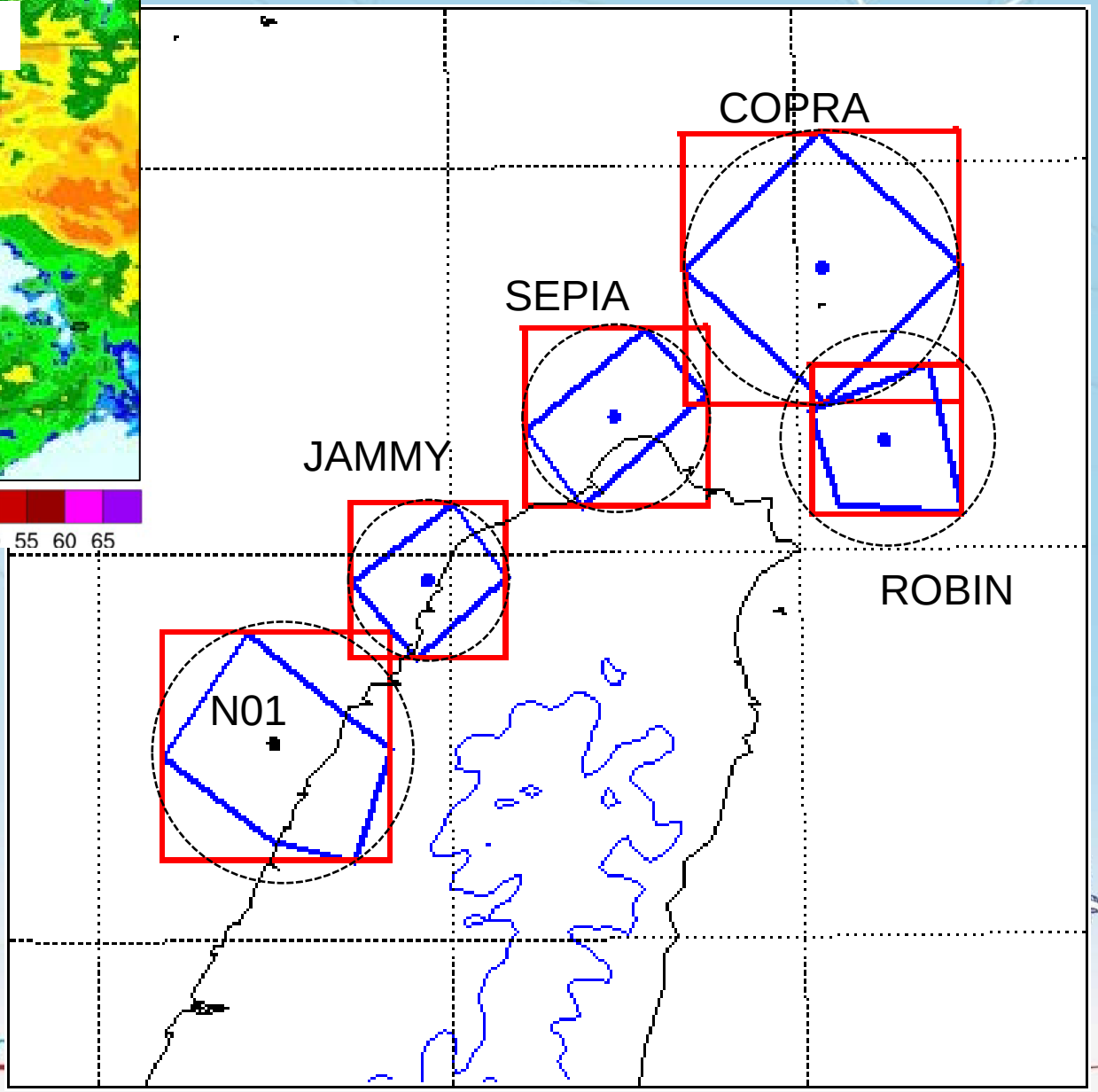
**Convective scale QPN at 2-km resolution**

# Applications

- **CWB NWP model output provides services in all aspects**
  - Hydrology, Flooding, and mudslide
  - Air quality prediction
  - Aviation services
  - Ocean current and wave
  - Search and Rescue Planning
  - Disaster prevention and decision making
  - …

# Air traffic control



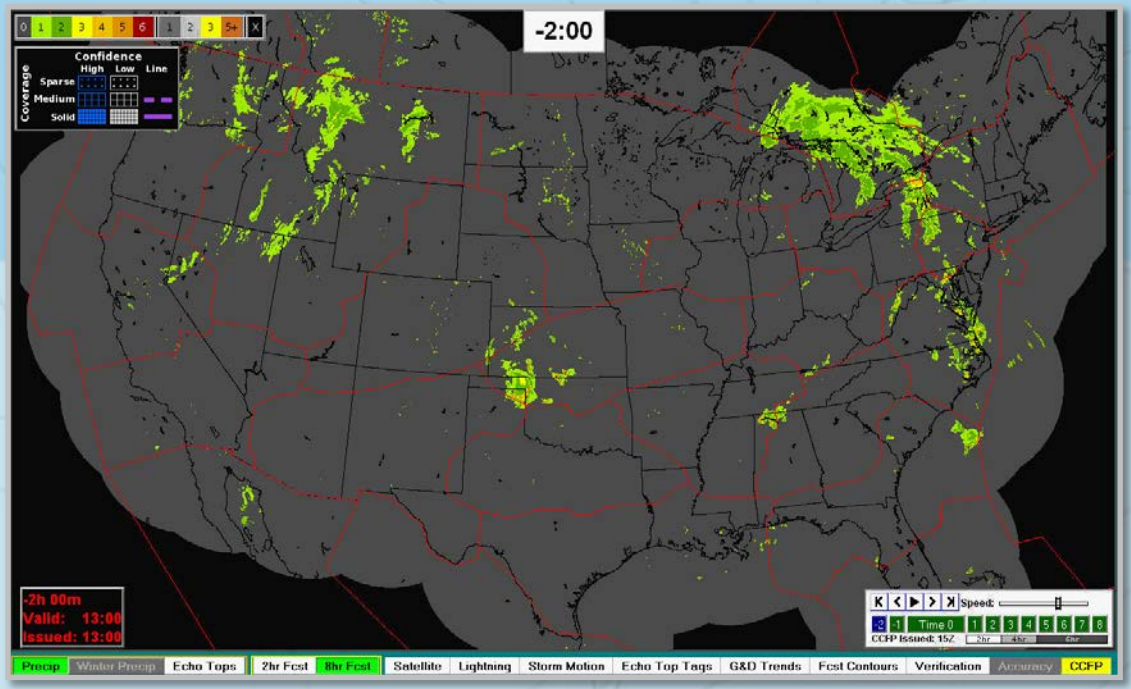




Weather Service Obser

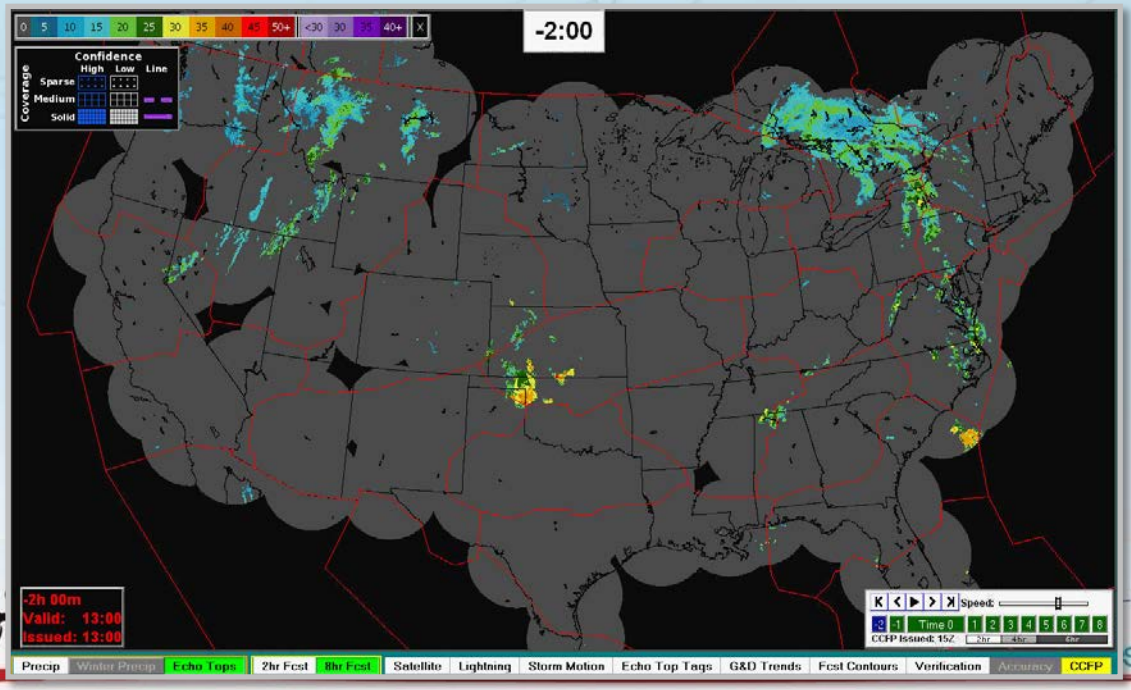
| 待命區 | 即時回波警示 | 17060404 | | | 17060405 | | | 17060406 | | | 17060407 | | | 17060408 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N01 | ● | | | | | | | | ● | ● | ● | | | | | |
| JAMMY | | | | | ● | ● | ● | | | | | | | ● | | ● |
| SEPIA | ● | | ● | ● | | | | | | ● | | | | | | |
| COPRA | | ● | | ● | | | | | | | | ● | | | ● | ● |
| ROBIN | | | | | ● | ● | | | | | | | | ● | ● | ● |

**流域管制警示 (含過去三個預報報資訊)**

- ●：最新預報達警示標準
- ●：前1報預報達警示標準
- ●：前第2報預報達警示標準




降水

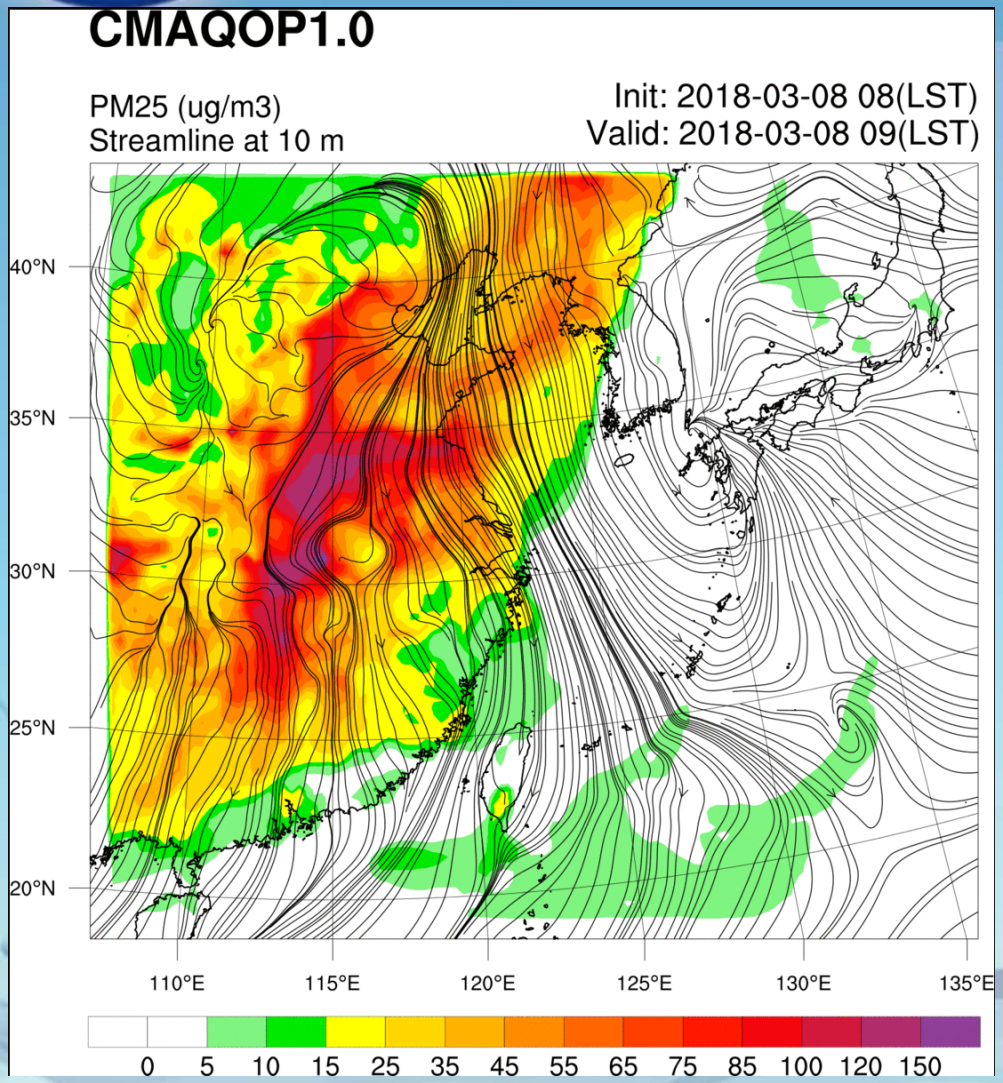


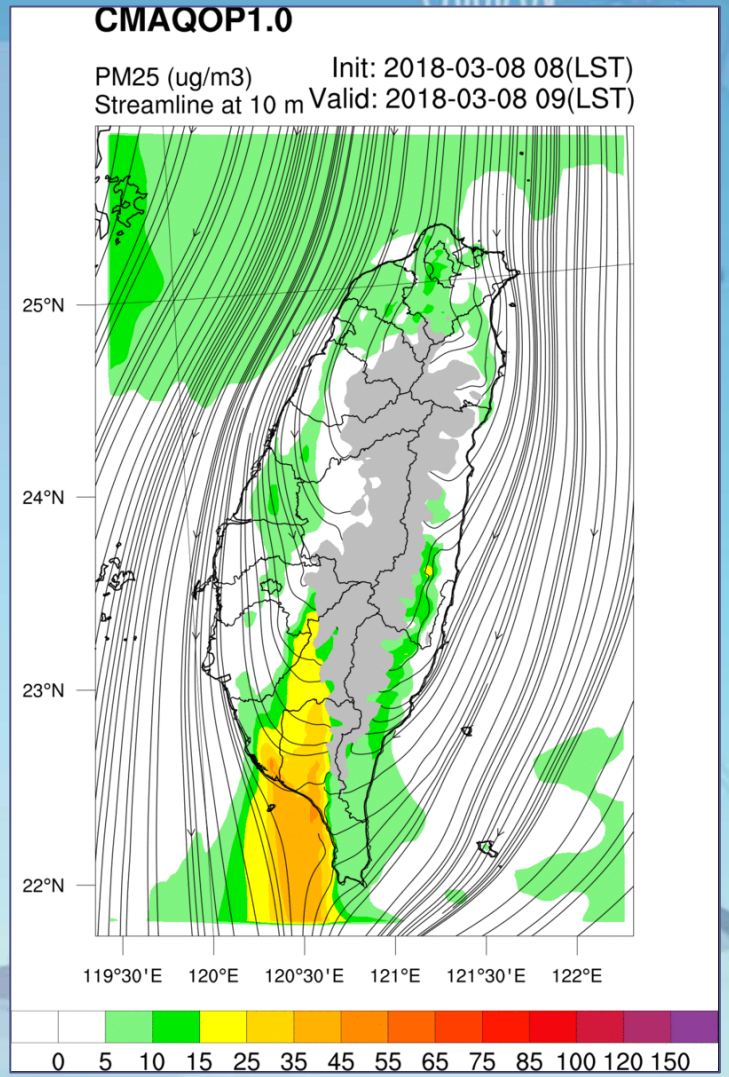

雲頂

**從過去的觀測**
**到未來的預報**

Marine Radar Astronomy

# 空氣品質預報應用-$PM_{2.5}$




產品範例：多采公司提供

# Applications

- **CWB NWP model output provides services in all aspects**
  - Hydrology, Flooding, and mudslide
  - Air quality prediction
  - Aviation services
  - Ocean current and wave
  - Search and Rescue Planning
  - Disaster prevention and decision making
  - …
  - **RENEWABLE ENERGY --- Let's work together**

# 展 望

- 綠電的成功是營運，營運的效能是建立在預測的基礎
- 綠電的預測必須要有專責單位，以提供電力調度參考之用
  - 須有上位的政策支援
  - 以防災/空污預報可以為例對比
- 對預測的誤差要有詮釋和論述的能力
  - 量化預測的誤差（包括發電量與氣象預測）
  - 分析誤差的來源，擬定改善的策略
  - 預測多準才是準？
    - 預測不確定性的存在是必然，需配合預測準確度，擬定因應策略與風險管理作為